Impact Assessment of a Far-field Tsunami Scenario on Christchurch City Infrastructure

A thesis
submitted in partial fulfilment of the requirements
for the degree of
Master of Science in Hazard and Disaster Management
at the
University of Canterbury
by

James Hilton Williams

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department of Geological Sciences
University of Canterbury
New Zealand

2016

Frontispiece

Tsunami damage on a coastal road from the 2015 'Illapel' earthquake tsunami

Coquimbo, Chile

Abstract

Tsunami have the potential to cause significant disruptions to society, including damage to infrastructure, critical to the every-day operation of society. Effective risk management is required to reduce the potential tsunami impacts to them. Christchurch city, situated on the eastern coast of New Zealand's South Island, is exposed to a number of far-field tsunami hazards. Although the tsunami hazard has been well identified for Christchurch city infrastructure, the likely impacts have not been well constrained. To support effective risk management a credible and realistic infrastructure impact model is required to inform risk management planning.

The objectives of this thesis are to assess the impacts on Christchurch city infrastructure from a credible, hypothetical far-field tsunami scenario. To achieve this an impact assessment process is adopted, using tsunami hazard and exposure measures to determine asset vulnerability and subsequent impacts. However, the thesis identified a number of knowledge gaps in infrastructure vulnerability to tsunami. The thesis addresses this by using two approaches: a tsunami damage matrix; and the development of tsunami fragility functions. The tsunami damage matrix pools together tsunami impacts on infrastructure literature, and post-event field observations. It represents the most comprehensive 'look-up' resource for tsunami impacts to infrastructure to date. This damage matrix can inform the assessment of tsunami impacts on Christchurch city infrastructure by providing a measure of damage likelihood at various hazard intensities. A more robust approach to tsunami vulnerability of infrastructure are fragility functions, which are also developed in this thesis. These were based on post-event tsunami surveys of the 2011 'Tohoku' earthquake tsunami in Japan. The fragility functions are limited to road and bridge infrastructure, but represent the highest resolution measure of vulnerability for the given assets. As well as providing a measure of damage likelihood for a given tsunami hazard intensity, these also indicate a level of asset damage.

The impact assessment process, and synthesized vulnerability measures, are used to run tsunami impact models for Christchurch infrastructure to determine the probability of asset damage occurring and to determine if impact will reach or exceed a given damage state. The models suggest that infrastructure damage is likely to occur in areas exposed to tsunami inundation in this scenario, with significant damage identified for low elevation roads and bridges. The results are presented and discussed in the context of the risk management framework, with emphasis on using risk assessment to inform risk treatment, monitoring and review.

In summary, this thesis A) advances tsunami vulnerability and impact assessment methodologies for infrastructure and B) provides a tsunami impact assessment framework for Christchurch city infrastructure which will inform infrastructure tsunami risk management for planners, emergency managers and lifelines groups.

Acknowledgements

I wish to firstly express my gratitude to my supervision team: Dr Thomas Wilson, Dr Matthew Hughes, Professor Tim Davies, Nick Horspool (GNS Science) and Dr Emily Lane (National Institute of Water and Atmospheric Science) for this opportunity, for believing in me and for pushing me to always go the extra mile! Dr Thomas Wilson has been a constant source of motivation. Thank you for your mentorship, and for always making yourself available for revisions and to solve my many research issues! I would also like to thank you for your role in sending me to present at the 8th Australasian Natural Hazards Management Conference in Perth. Dr Matthew Hughes, beyond making me a semi-competent GIS analyst, thank you for all the GIS assistance and methodology development as well as for all your support. Professor Tim Davies has been my first point of call for thesis revisions, for which I am very appreciative. I would like to thank Nick Horspool for coming up with great research projects, for calibrating my tsunami damage matrix and especially for including me in your post-event survey team following the 2015 'Illapel' earthquake tsunami in Chile. I wish to also express appreciation for Dr Emily Lane, for your support and for providing excellent tsunami hazard models, on which this impact assessment is based.
I also wish to thank Dr Marion Gadsby (Environment Canterbury) and James Thompson (Canterbury Civil Defence and Emergency Management Group) for the project opportunity, research direction and especially to Dr Marion Gadsby, on behalf of Environment Canterbury, for the financial support on this project.

To my fellow tsunami researchers: Lina Le and Finn Scheele. Thank you both for your collaboration and discussions as well as your assistance when I was pressed for time!

I also wish to acknowledge the other members of the tsunami survey team I travelled to Chile with: Ryan Paulik, Richard Woods and Richard Mowl, for the tsunami and infrastructure education, conference opportunities and discussions of future research.

Last but not least, I want to thank my friends and family. Especially to Mum and Dad for all their support over the years and to my partner Harriette for all the proof reading, support (emotional and financial) and most importantly for holding me together at the end!

Contents

List of Figures

List of Tables

Chapter 1

Introduction and Hazard Background

1.1 Context of study

Tsunami have the potential to cause significant disruptions to society including damage to infrastructure, critical to the every-day operation of society. Christchurch city, situated on the eastern coast of New Zealand's South Island, is exposed to a number of far-field tsunami hazards sourced from the Peruvian-Chilean subduction zone off the South American coast. Although the tsunami hazard has been well identified for Christchurch city infrastructure, the likely impacts have not been well studied. Infrastructure vulnerable to tsunami includes transport corridors, water networks, telecommunications, port facilities and the electricity network (Centre for Advanced Engineering 1997). Effective risk management is required to reduce the potential tsunami impacts to Christchurch city infrastructure and in support of this, a credible and realistic infrastructure impact model is required to inform risk management planning.

Infrastructure is vital to the post-disaster recovery and normal operation of society. Transportation networks play an important role in evacuation and provision of aid (Frangopol & Bocchini 2012; Nakanishi et al. 2014; Saatcioglu 2007). Transportation also provides the means to access damaged sectors of other infrastructure networks and accelerate recovery. Many infrastructure networks are interdependent, (e.g. electricity for wastewater treatment) (Centre for Advanced Engineering 1997) and undamaged buildings may be uninhabitable without infrastructure services.

Damage to infrastructure can make up 20% of the total economic cost of a tsunami disaster, mostly attributed to transport asset impacts (Marchand et al. 2009). It is therefore necessary to mitigate tsunami impacts prior to the event (including site exclusion and design planning) and/or to restore the functionality of these networks as soon as possible following a tsunami. International case-studies have shown that the impacts associated with a tsunami can be reduced through appropriate risk reduction techniques (Horspool & Fraser 2015). The scale and spatial distribution of tsunami impacts on infrastructure will determine the impacts on population and the efficiency of post-disaster relief and recovery (Gill et al. 2015). This means that a credible and realistic infrastructure impact model is required to improve the management and mitigation of tsunami risk in Christchurch.

1.2 Research Aims and Objectives

The aim of this research is to assess the impacts on Christchurch city infrastructure from a hypothetical South America-sourced tsunami, by developing methodology for an infrastructure impact model.

The objectives of the present research are to

- Review and identify the impacts on infrastructure following significant tsunami reported in international case studies, from relevant literature and field observations.
- Implement impact assessment processes to prove the effectiveness of multi-risk analysis software concepts for tsunami impact modelling on infrastructure.
- Provide a credible and realistic tsunami impact model, based on existing hazard models, for a hypothetical tsunami scenario.
- Assess the tsunami exposure and impacts on Christchurch city infrastructure.

This research has been conducted in parallel with that of Scheele (2016), which provides a tsunami impact assessment of Christchurch city buildings from the same hypothetical scenario as that herein. The research was requested jointly by the Canterbury Civil Defence and Emergency Management (CDEM) group, Environment Canterbury and the National Institute of Water and Atmospheric Research (NIWA). A $5,000 scholarship was awarded by Environment Canterbury to conduct this study. Both studies are in support of a Tier 4 national Civil Defence and Emergency Management (CDEM) exercise taking place in 2016 (Ministry of Civil Defence and Emergency Management 2016) and this research has been commissioned in part to contribute towards the realism of the given scenario for participants.

1.3 Risk Management Framework

This section presents the risk management framework and how it acts as the conceptual framework for this study. The risk management framework (Figure 1.1) was developed to provide a systematic and robust approach to reducing risk through: risk identification, risk analysis, risk evaluation, and risk treatment (Standards New Zealand 2009). The focus of this thesis is to assess impacts on infrastructure and this is achieved by embedding an impact assessment process within the risk analysis stage of the risk management framework.
A credible tsunami impact model for infrastructure will provide the means to better manage and mitigate the risk from a far-field tsunami in Christchurch city. It would serve to isolate vulnerabilities in infrastructure networks, providing information enabling emergency managers and planners to implement appropriate mitigation strategies.

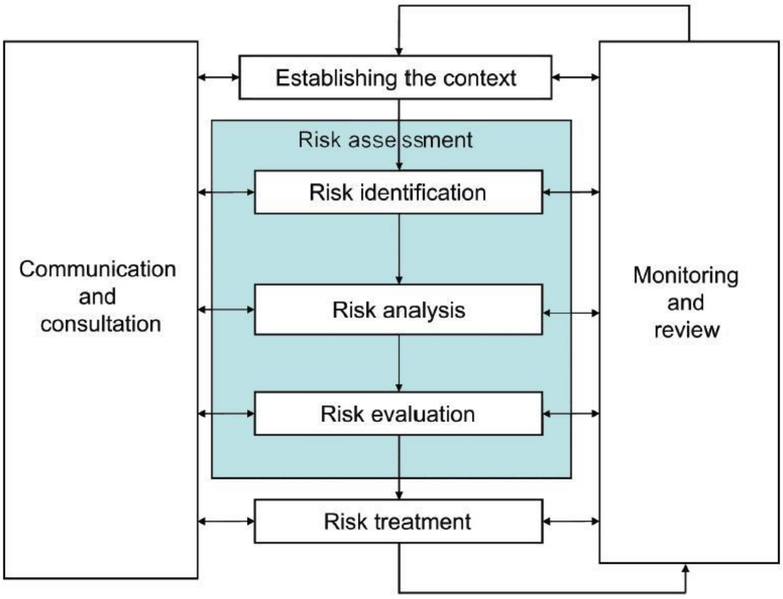

Figure 1.1: Risk management framework (Standards New Zealand 2009)

The terms used in the risk management framework are defined by the following equation (modified from Power 2013):

Risk = Hazard x Vulnerability

Hazard is defined as the interaction between society (exposure), an extreme natural phenomenon at a certain magnitude (intensity), with a given frequency (return period), which has potential to cause negative effects. Vulnerability is the degree to which elements (e.g. infrastructural assets) can be damaged due to the hazard. Risk is the probability that damage to elements will occur as a result of the hazard based upon an asset's vulnerability to the hazard. However, in the context of the impact assessment adopted in the present research, 'impact' can be defined as the potential consequence of the given risk. This thesis uses a level of service (loss of services or no loss of services) to describe tsunami impacts on infrastructure, based on analysed levels of risk in Chapter 4.

1.3.1 Risk Identification

Once the context and objectives are established, the risk management framework progresses toward risk identification. In the context of this research, this step involves identifying all potential tsunami hazards and determining their potential impacts on infrastructure. This is achieved by reviewing literature on previous tsunami events worldwide. It involves recognising the range of hazards a society is exposed to and what aspects are vulnerable. Societal aspects include people, buildings and infrastructure (Sword-Daniels et al. 2014; Power 2013) with the latter being the focus of this research. It also involves the determining of constraints, including data limitations. A review of infrastructure vulnerability literature is presented in Chapter 2.

1.3.2 Risk Analysis

The risk analysis stage of the risk management framework focuses on developing an understanding of risks, so they can be compared and ranked (Standards New Zealand 2009). In the context of the present research this means determining the vulnerability of exposed infrastructural assets to tsunami hazards.

These analyses can be either probabilistic, deterministic or aspects of both.
Deterministic scenario-based assessments use hypothetical hazard scenarios, based on models or previous events to determine the impact of hazards on the given asset(s). These often implement worst-case scenarios and provide a definitive impact value (e.g. damaged/not damaged). These assessments are often limited by subjective expert opinions resulting in: risk

uncertainty; no likelihood of risk/impacts; and focusing on only a single scenario (Borrero & Goring 2015). These limitations can in certain circumstances be addressed with a probabilistic approach. Probabilistic risk assessments are used to define the probability of a hazard occurring and its associated damage from a range of scenarios, with limited subjective input. To determine the degree of damage that can occur in each scenario, fragility functions can be incorporated into probabilistic risk assessment.

Fragility functions are often empirical probabilistic functions which communicate the probability of an asset suffering a given level of damage, at each hazard intensity (e.g. inundation depth, flow velocity etc.) and are commonly presented as a series of fragility curves (Power 2013; Horspool & Fraser 2015). They are developed through observations either in a controlled experimental setting or in the field (e.g. a post-event survey). These functions are helpful during risk treatment, as they can define which conditions cause impacts to occur and where mitigation strategies may help reduce these impacts, and therefore risk. Fragility functions are discussed further in Chapter 2.

A deterministic scenario-based approach is taken for this research, using a hypothetical inundation scenario, however it also implements probabilistic assessments of asset vulnerability to achieve this. An impact assessment process can be embedded within the risk analysis stage of the risk management framework, which is outlined in Section 1.4. The results of this analysis will yield values describing an asset's probability of incurring damage in the given scenario, or the probability of reaching or exceeding a given level of damage (damage state).

1.3.3 Risk Evaluation

Risk evaluation compares various risks to determine what actions could be taken to reduce impacts and therefore risk (Standards New Zealand 2009; Power 2013). Ranking risk as acceptable, tolerable, and/or unacceptable is crucial to tsunami impacts mitigation. In the context of this thesis, this step involves constraining areas of high priority for mitigation based on the results of a tsunami impact assessment on Christchurch city infrastructure, and outlining potential mitigation strategies.

1.3.4 Risk Treatment

The final stage of the risk management process is risk treatment. This involves determining how best to reduce the vulnerability of exposed assets and/or the hazard. Impacts, and therefore risk, can be reduced through the application of various mitigation strategies, developed through the integration of field or laboratory analyses (Horspool & Fraser 2015; Power 2013; Palliyaguru & Amaratunga 2008; Gill et al. 2015). They include land management legislation, relocation of assets, improved construction standards, hazard monitoring and societal education.

The results of a tsunami impact assessment on Christchurch city infrastructure can be used to provide emergency managers and planners with a metric on which to base response and mitigation strategies and it also provides potential and recommended mitigation strategies, for exposed infrastructural assets. This can lead to a reduction in future tsunami impacts on Christchurch and therefore a reduction in risk.

1.3.5 Monitoring and review

During the course of the risk assessment process it is crucial to implement up-to-date information. The methods used in this research are designed so that input parameters can be substituted with more relevant and/or up-to-date data to improve the subsequent impact assessment. The methods themselves should also be scrutinized if new techniques are developed that would provide a more relevant/accurate risk assessment. Monitoring and review in turn provides a better means by which to evaluate, and therefore mitigate, risk.

1.3.6 Communication and Consultation

As with monitoring and review, it is crucial to communicate to, and consult with, relevant stakeholders throughout the risk assessment process. This is especially important for emergency managers and planners who will have a direct role in the risk treatment stage of the risk assessment process. Ensuring that impact and risk assessments are geared towards what these organisations require will ensure the best means by which to evaluate and therefore mitigate risk. The present research has maintained constant communication and consultation with leading and relevant research, emergency management and planning stakeholders. These include Canterbury Civil Defence and Emergency Management, Environment Canterbury, the National Institute of Water and Atmospheric Research, GNS Science and the University of Canterbury.

1.4 Impact Assessment Process

The core of this research is impact assessment, which, as mentioned previously, can be embedded within the risk analysis stage of the risk management framework (Section 1.3.2 and Figure 1.1). It can be adopted to model the impacts on Christchurch city infrastructure, and subsequently used to inform mitigation and response strategies to reduce impacts and therefore risk.

The impact assessment process (Figure 1.2) is a commonly adopted approach to modelling disaster impacts especially in multi-hazard and loss modelling software. One example is RiskScape (GNS & NIWA 2015) which is available for New Zealand-specific risk and impact modelling. One objective of this research is to use concepts from RiskScape to prove the process effective, hence methods presented in Chapter 2 incorporate this.

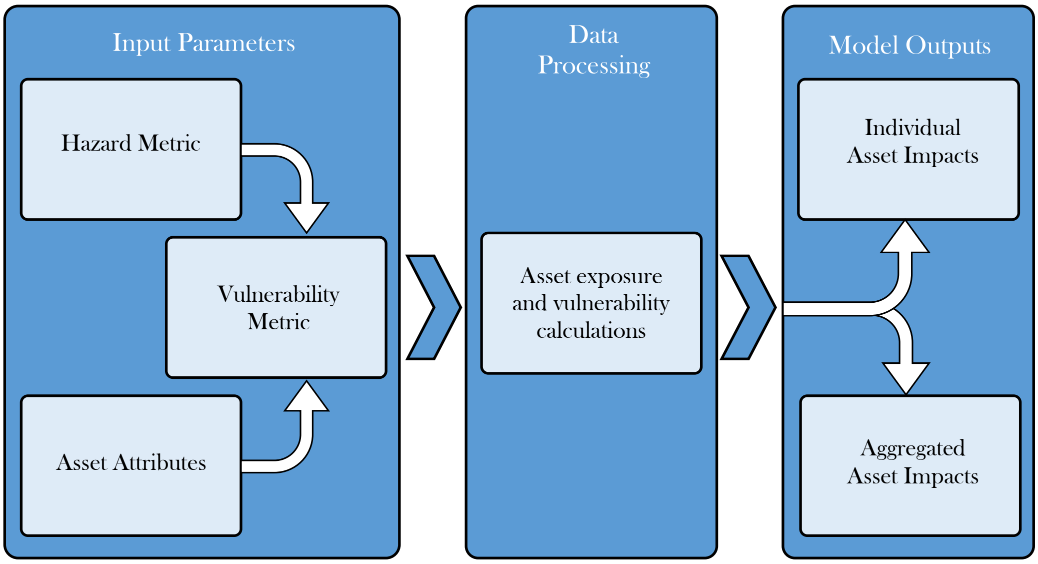

Figure 1.2: Impact assessment process (modified from GNS & NIWA 2015)

Impact assessments can be either ex ante or ex post (Power 2013). Ex ante assessments are conducted prior to an event using deterministic or probabilistic analyses and are aimed at predicting impacts in order to reduce risk. Ex post assessments are undertaken following a specific event as a post-disaster survey. They are commonly used to verify/validate scientific models as well as prioritising relief and rehabilitation efforts (Power 2013). The focus of this research is an ex ante impact assessment on Christchurch city infrastructure, however ex post impact assessment data are used to inform the approach (especially for vulnerability assessment in Chapter 3). The approach developed in this research is suitable for integration/input to RiskScape.

All data used in the development of impact assessment parameters can be analysed qualitatively, quantitatively or semi-quantitatively, each with advantages and disadvantages. Qualitative analyses are descriptive rather than numerical and often use coarse data or expert opinions to derive or categorise damage, such as the tsunami damage matrix developed in Chapter 2. They are often used with low volumes of data and/or too many uncertainties to warrant quantitative methods. Semi-quantitative analyses use a numerical evaluation of quantitative impact assessment by ranking risk. These rankings are not necessarily any more realistic than a qualitative analysis, however they provide a more rigorous and consistent approach to comparing risk values and mitigation techniques (Power 2013; Standards New Zealand 2009). Quantitative assessments can be either deterministic or probabilistic (as outlined in Section 1.3.2) and use numerical values for both risk and impact using modelled, experimental or historic data (Standards New Zealand 2009; Power 2013). Quantitative input parameters provide the most in-depth results for an impact assessment, depending on the data quality of other input parameters. These assessment types are discussed further in Chapter 2. The data processing stage of the impact assessment process (Figure 1.2) is outlined in Chapter 2. Input parameters are outlined below and discussed further in Chapters 2 and 3.

1.4.1 Hazard metric

To quantify impact, a hazard characteristic must be determined on which to base the assessment (Figure 1.2), and to apply a measure of magnitude to exposed assets (GNS & NIWA 2015; Power 2013; Thywissen 2006). In the case of this research, tsunami inundation depth is used as a hazard metric. Flow velocity is another tsunami hazard metric used in impact assessments. A measure of hazard frequency can also be used in an impact assessment (although it is not in the present research). This is done by associating each hazard magnitude with a specific return period or vice-versa (Thywissen 2006; Power 2013). Numerical modelling can be used to compute tsunami propagation, the resolution of which is often determined by the resolution of local topographic data.

1.4.2 Exposure Asset Attributes

Exposure is also required to quantify tsunami impacts (Figure 1.2). It can be defined as the number of elements that could be affected by the given hazard. These can include people, building and, in the case of this research, infrastructural assets (Schmidt et al. 2011; Power 2013). There is a spatial-temporal relationship between the elements at risk and the hazard magnitude, based on a chosen hazard metric. As well as spatial exposure, each asset also has a set of attributes that can be used to describe its potential to withstand a given hazard, such as construction type, construction materials, use category, floor height etc.

Compiling infrastructure-specific data can be challenging as many data are owned by private organizations, in inconsistent formats and in some cases with commercial security restrictions (Power 2013).

1.4.3 Vulnerability Metric

Vulnerability can be defined as the potential for negative effects to occur to a given asset/attribute. A vulnerability metric determines the severity of the impact by magnitude of the local hazard and an asset's potential, or lack thereof, to resist it (Papathoma & Dominey-Howes 2003; Marchand et al. 2009; Porter n.d.; Power 2013). Common quantitative vulnerability metrics include fragility functions (see Section 1.3.2), which describe the probabilistic relationship between hazard intensity and damage (Reese et al. 2011; Power 2013; Horspool & Fraser 2015; Mas et al. 2012). Qualitative vulnerability metrics include damage matrices which provide a descriptive measure of vulnerability (e.g. high, medium, low). The use of local data is preferential in an impact assessment as, in the case of infrastructure, assets and systems are more comparable (in design and operation) than with overseas equivalents.

The vulnerability metric combines hazard and exposure metrics to quantify impacts on the given element (see Figure 1.2), which in the context of this research is tsunami impacts on Christchurch city infrastructure.

1.5 Tsunami Hazard Background

The objective of this section is to define tsunami and the associated hazard including potential damage styles and the New Zealand and Christchurch specific tsunami hazard.

When a series of waves causes sea level to fluctuate more rapidly than a single tidal cycle, it is considered to be a tsunami (Power 2013; Horspool & Fraser 2015). These are usually generated by large area sea floor disturbances which have the capacity to displace the entire water column above, such as an earthquake, submarine landslide or volcanic activity (Power 2013; Horspool & Fraser 2015). They can also occur from large area displacements on the water surface, such as a meteorite impact or landslide (Power 2013). The speed and height of tsunami waves at a given location depend on the magnitude of the trigger event, the distance from source and the directivity of wave approach (Gill et al. 2015; Horspool & Fraser 2015; Fraser et al. 2014; Jin & Lin 2011; Power 2013). Tsunami waves can reach a shoreline in seconds-to-minutes if the source event is proximal to the coast, or many hours if from a far-field source (Figure 1.3). Tsunami can be defined by their travel times as either local (< 1 hour), regional (1-3 hours) or far-field/distal (> 3 hours).

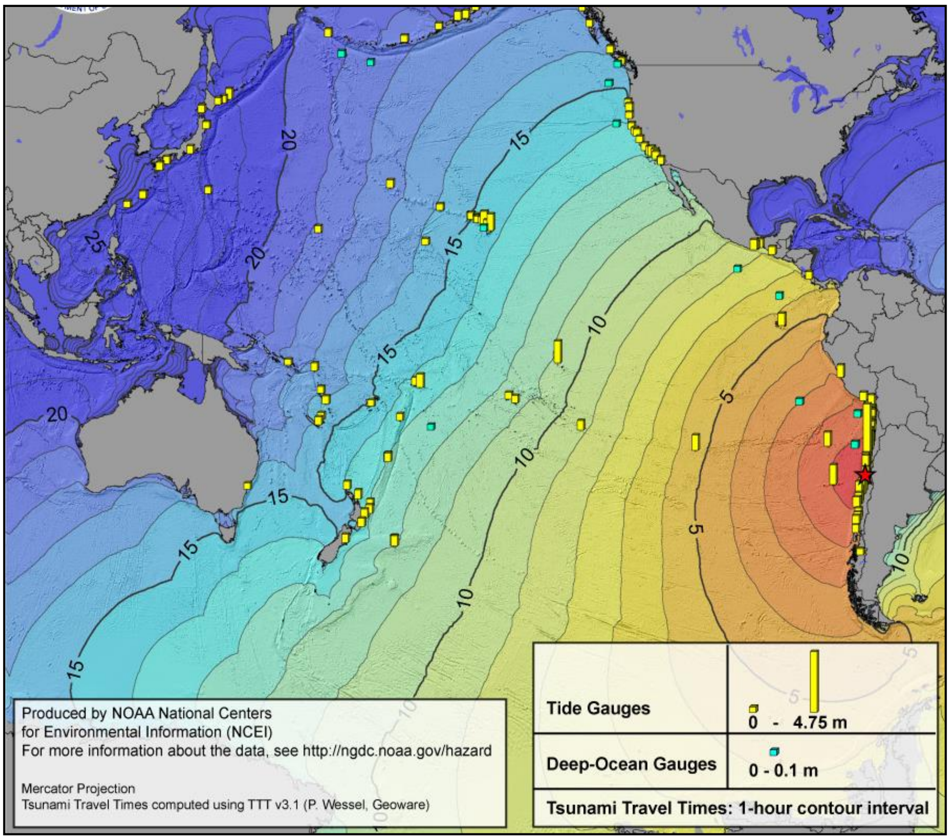

Figure 1.3: Observed water heights (yellow and blue bars) and computed tsunami travel times for 2015 'Illapel' earthquake tsunami (National Oceanic and Atmospheric Administration 2015)

Once a tsunami reaches a coastline the waves slow and their wavelength decreases (see Figure 1.4), and the water column will either flow long distances inland (e.g. over low, flat topography), or become relatively confined nearer to the coast (e.g. when restricted by steep coastal topography). Tsunami have been the cause of many international disasters historically,
Table 1.1 presents those from the past two decades.

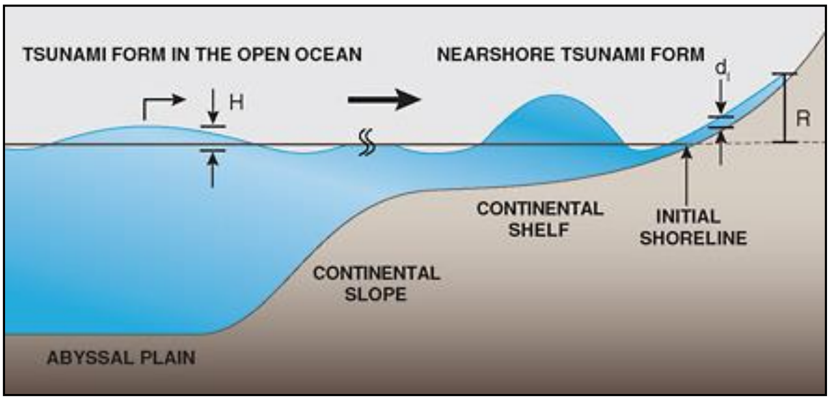

Figure 1.4: Tsunami terminology: H = tsunami wave height; R = run-up height; d_i = inundation depth (Division on Earth and Life Studies et al. 2011)

Table 1.1: Tsunami resulting in casualties in the past 2 decades

Location	Year	Source	Casualties	Reference
Papua New Guinea	1998	Papua New Guinea	2,200	*(USGS 2015)*
Indian Ocean	2004	Sumatra	230,000	*(Mulligan & Nadarajah 2011)*
Java	2006	Java	600	*(USGS 2015)*
Solomon Islands	2007	Solomon Islands	52	*(USGS 2015)*
Samoa	2009	Samoan islands	189	*(Okal et al. 2010)*
Chile	2010	Chile	525	*(Fritz et al. 2011)*
Sumatra	2010	Sumatra	408	*(USGS 2015)*
Japan	2011	Japan	15,891	*(Yeh et al. 2013; USGS 2015)*
Solomon Islands	2013	Solomon Islands	10	*(USGS 2015)*
Chile	2015	Chile	13	*(Gaurdian News and Media Limited 2015)*

1.5.1 Tsunami Damage Styles

The behaviour of a tsunami may vary spatially across an area. It is therefore important to understand how tsunami cause damage, in order to determine the impacts they may have on infrastructural assets. Power (2013) outlines the different styles of tsunami damage as primary and secondary impacts. Primary impacts are based on forces caused by the flow of water (both hydrostatic and hydrodynamic impacts), while secondary impacts involve the movement of objects by the flowing water. The following is a summation of the different styles of tsunami damage typically observed.

1.5.1.1 Inundation and Contamination

Areas exposed to tsunami are generally limited to relatively narrow bands along a coast, often less than a few km from the initial shoreline (Yeh et al. 2013). The distribution of tsunami inundation is dependent on topography as well as wave height (see Figure 1.4). Run up of a tsunami will be determined by the scale of the initial displacement on the water column (wave height), the distance from its source (energy lost) and the local topography. This implies that near-source tsunami would have greater wave heights at a given coast than far-field tsunami of the same initial wave heights. Geomorphic features such as beach terraces, sea cliffs and thick vegetation will result in restricted inundation extents (but often higher run-up), whereas areas of tidal flats, mud flats, estuaries and river inlets have been observed to suffer greater areas of inundation (Chandrasekar & Ramesh, 2007). Inundation on its own can cause minor-to-significant impacts, including to soil conditions (from salt contamination), control panels, fuse boxes and structures (from intrusion of moisture and fine sediments; e.g. Figure 1.5) (Power 2013).

Figure 1.5: Fine sediments which were entrained in tsunami flow, mark an inundation depth indicator (below arrows) on a building in Coquimbo, Chile, following the 2015 'Illapel' earthquake tsunami

1.5.1.2 Hydrodynamic Forces

The flow depth and velocity of a tsunami directly influence the hydrodynamic pressure that it can apply to structures and surfaces. These involve dragging (horizontal), erosion (scouring) and buoyancy (vertical lifting) induced deformation of structures, and occur during advancing wave fronts and/or retreating flows (Power 2013). The positioning of structures and topography can increase or decrease the hydrodynamic forces of a tsunami. Debris in the flowing water can also influence the hydrodynamic forces of a tsunamis. An increase of pressures would occur when debris hinders the flow of water (e.g. beneath a bridge). Comparatively, wall collapse can create a jet flow through building interiors (e.g. Figure 1.6).

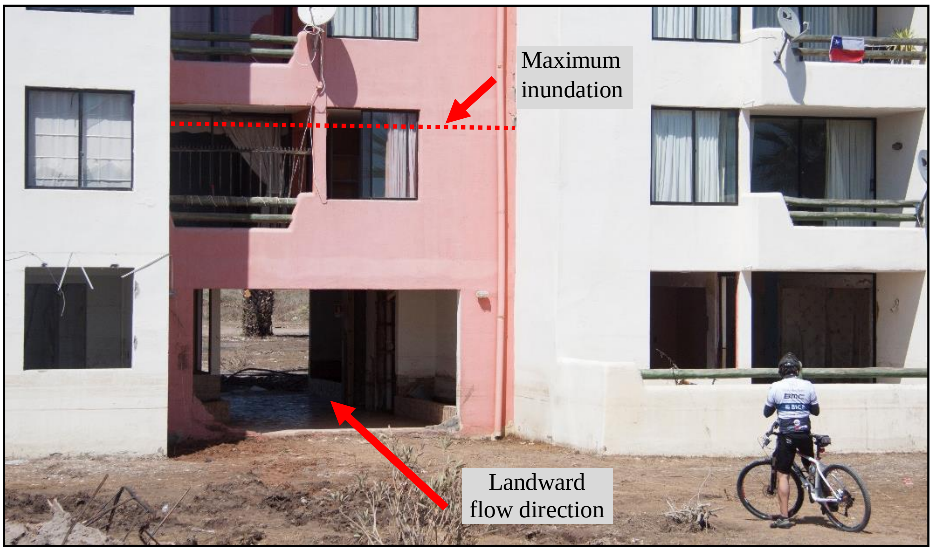

Figure 1.6: Increased tsunami velocity created by confined flow resulted in complete internal and external wall blowout in an apartment building in Coquimbo, Chile, during the 2015 'Illapel' earthquake tsunami

1.5.1.3 Debris impacts

Debris impacts are a significant cause of tsunami damage to structures (e.g. Figure 1.7). Unlike inundation depth, entrained debris behaviour is difficult to measure or quantify directly and hence, is often inferred from post-event observations (Reese et al. 2011; Naito et al. 2014). Debris transport depends on the size of debris, topography, inundation, velocity, flow direction, and the layout of surrounding structures.

Building construction and spacing play an important role in debris transport through urban areas. In industrial areas where steel and concrete construction is typical, buildings are generally able to withstand the hydrodynamic forces generated by tsunami and can therefore act as barriers to debris transport, while also confining flows, to result in greater depths and velocities therefore producing increased probability of debris mobilisation. However, as Naito et al. (2014) and Reese et al. (2011) acknowledge, the fact that a structure can stop debris transport also means that it is subject to debris impact damage. This may in turn cause eventual structural collapse, thus releasing additional debris into the water flow, which is where debris dispersal becomes complex.

Figure 1.7: Debris impact damage to a reinforced masonry building in Coquimbo, Chile, following the 2015 'Illapel' tsunami earthquake

1.5.1.4 Soil Instability

Scour of soils can occur in high velocity tsunami flows (Figure 1.8) and are often associated with the retreating wave. Soil instability is not exclusively associated with fast tsunami flows and has been observed in areas that were assumed to have minimal flow velocities (Yeh et al. 2013). This phenomenon can involve the lifting of asphalt surfaces, especially on roads, harbour quays, and parking lots at low elevations near the shore. This can be caused by liquefaction and subsidence, two impacts usually associated with seismic events. During tsunami inundation, soil top layers are compressed, resulting in an increase in pore pressure and total normal stress of the entire soil profile. Consequently as tsunami water retreats, the soil will decompress and the slow rate of pore pressure dissipation creates a vertical gradient of excess pore pressure within the soil. Once this excess pore pressure gradient equals or exceeds the buoyant specific weight of the bulk saturated soil it can suffer a complete loss of shearing force resistance, resulting in liquefaction (Yeh et al. 2013; Mas et al. 2012).

Figure 1.8: Collapsed pavement due to scoured base material in Coquimbo, Chile from the 2015 'Illapel' earthquake tsunami

1.5.1.5 New Zealand and Christchurch Tsunami Hazard Assessment

New Zealand has large exposure to tsunami hazards from multiple sources, but has little direct experience (Gill et al. 2015), because human habitation (and recording of tsunami observations) is relatively recent (see Table 1.2). New Zealand has experienced multiple large tsunami (>10 m at the coast) based on the geological record, and since European settlement approximately 10 tsunami have been recorded exceeding 4 m heights at the coast (Gill et al. 2015). Although damaging tsunami happen infrequently, they can cause substantial fatalities and property damage in affected areas when they do occur. Figure 1.9 by Power (2013), represents New Zealand's tsunami hazard for the 2,500 year return period at the 84th percentile. Note that Christchurch and Lyttelton Harbour are both >12 m tsunami height at the coast.

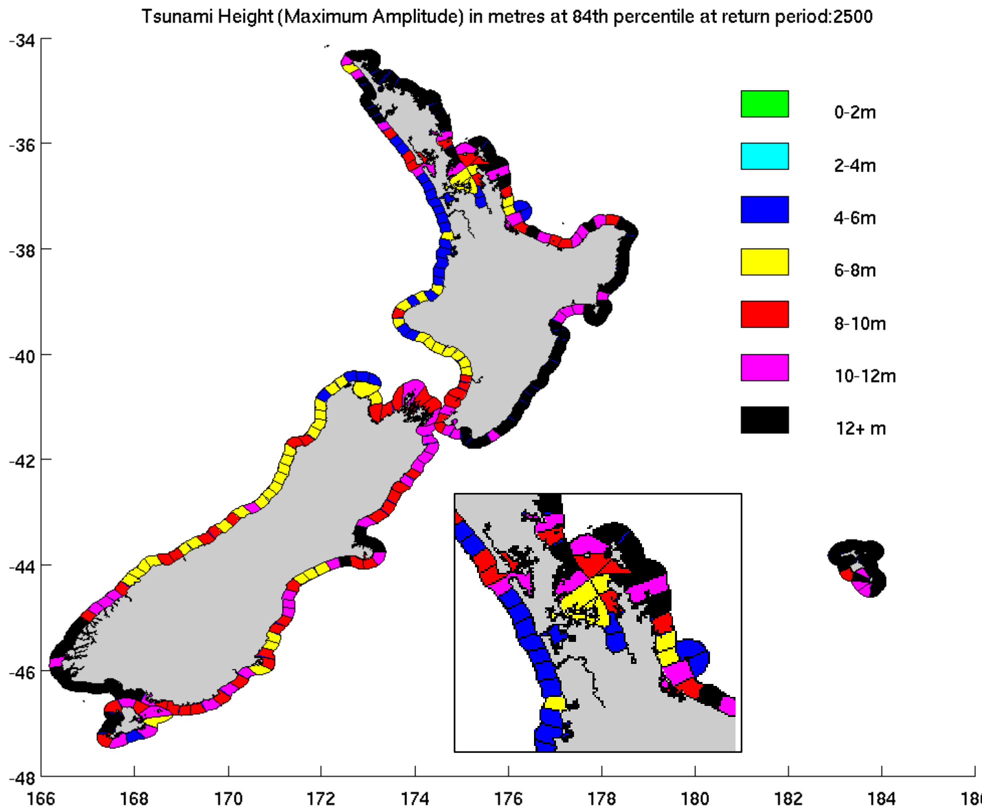

Figure 1.9: Expected maximum tsunami height in metres at 2,500 year return period, shown at the 84th percentile of epistemic uncertainty (Power 2013)

There have been a number of recorded tsunami in Christchurch since European settlement. Table 1.2 shows historic tsunami that have impacted Christchurch, all of which were sourced from South American submarine earthquakes.

Table 1.2: Historic Christchurch Tsunami, 1868 - 2010

Year	**Source**	**EQ Magnitude**	**Reference**
1868	Peru	Mw=9.1	*(De Lange & Healy 1986; Lane et al. 2012; Goff & Chagué-Goff 2012)*
1877	Chile	Mw=8.7	*(De Lange & Healy 1986)*
1960	Chile	Mw=9.5	*(Goff & Chagué-Goff 2012; Lane et al. 2012; Power 2013; Borrero & Goring 2015)*
2010	Chile	Mw=8.8	*(Lane et al. 2012)*
2015	Chile	Mw=8.3	*(National Oceanic and Atmospheric Administration 2015)*

Christchurch is located on the western edge of the Pacific Ocean (Figure 1.10) and is subjected to local, regional and distal source tsunamis (Lane et al. 2014). Goff & Chagué-Goff (2012) have identified up to seven paleo-tsunami likely to have impacted the Christchurch area over the past approximately 6,500 years. There was more than one possible paleo source identified for each, however it was concluded that the likely source for most, if not all, were South American subduction zone events as opposed to local or regional sources. Power (2013) estimates the tsunami hazard for Christchurch to be >9.5 m and >12.5 m wave heights at the coast at the 50th and 84th percentiles respectively for a 2,500 year return interval. Power (2013) also estimates Christchurch's most likely tsunami source for both a 2,500 and 500 year event, at the 50th percentile, is a Peru subduction zone event. Although historically Chile has proven the more common tsunami source for Christchurch, a Peru subduction zone source is considered a larger hazard than an equivalent Chile subduction zone event (Figure 1.11).

Figure 1.10: Map showing central and eastern Christchurch, New Zealand

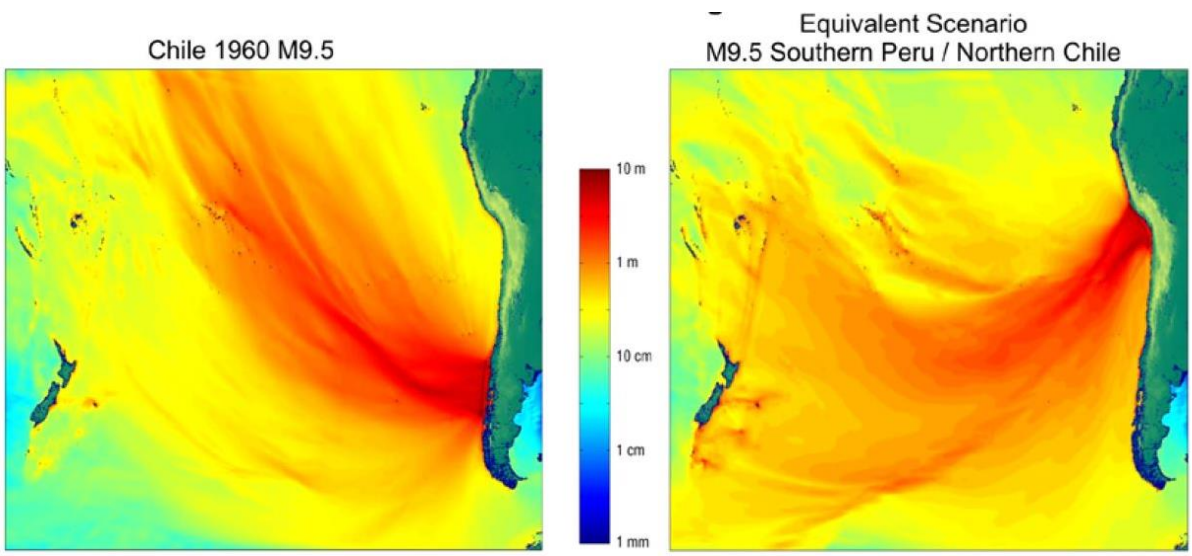

Figure 1.11: Comparison of 1960 Chilean tsunami wave height propagation model and equivalent Peru Scenario illustrating the effect that directivity and great circle routes can have on maximum wave heights in New Zealand (Power 2013)

Lane et al. (2014) have numerically modelled the tsunami hazard to Christchurch using an equation of fluid motion, basing it on a Mw 9.485 earthquake from a Peru subduction zone source (Figure 1.12). It represents the tsunami hazard for a 2,500 year return period at the 84th percentile confidence interval (Lane et al. 2014; Power 2013). There are previous tsunami hazard models for Christchurch with a range of sources and magnitudes, but these do not account for the changes in topography following the 'Canterbury earthquake sequence' which has impacted Christchurch since late 2011. The recent models represent the highest resolution tsunami inundation and velocity models for Christchurch and will be used as a hypothetical scenario for the present impact assessment. Appendix 7.1 covers the specifics of these models.

The modeling by Lane et al. (2014) assumes fixed topography, meaning it does not take into account the progressive scouring of features such as coastal dunes, and any consequential changes to the associated velocity and inundation. Hart & Knight (2009) found that Christchurch coastal dunes, from South Shore to the Northern Christchurch coast, currently provide a high degree of protection from potential tsunami of heights up to 6 m above mean sea level, irrespective of gaps in the dunes (Appendix 7.2). However, once a dune is breached, erosion is expected to widen the area of breaching significantly. This will impact the distribution of tsunami inundation.

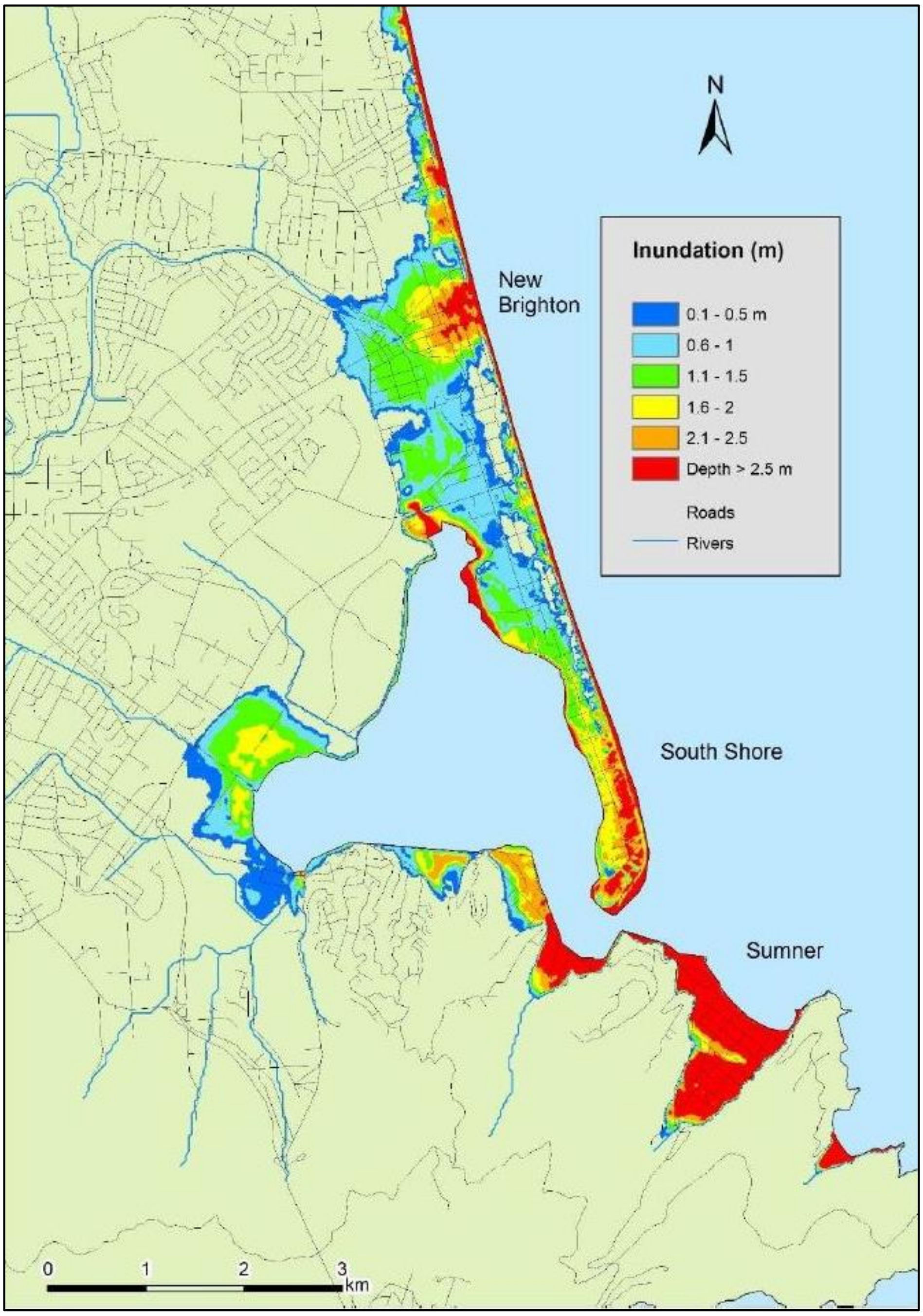

Figure 1.12: Modelled tsunami inundation depths for a 1:2500 year return Peru subduction zone event in Christchurch (from Lane et al. 2014)

1.6 Research Methodology and Thesis Structure

The methodology used in this thesis follows the risk management framework of risk identification, risk analysis risk evaluation and risk reduction (Figure 1.1). Within the risk analysis stage a combination of probabilistic and deterministic approaches follow an impact assessment process which implements qualitative and quantitative data for an ex ante tsunami impact assessment on Christchurch city infrastructure.

The risk identification stage was undertaken by identifying the various hazards associated with tsunami and the potential styles of damage (Chapter 1).

Fragility curves, required for an impact assessment, are largely lacking for tsunami impacts on infrastructure, therefore the risk analysis stage was undertaken in three parts.

1. Firstly a literature review of available quantitative fragility functions was used to determine infrastructure vulnerability to tsunami hazards, including inundation depth, flow velocity and debris impacts (Chapter 2).
2. Secondly a qualitative damage matrix was developed to determine infrastructure vulnerability of assets that lacked associated fragility curves (Chapter 2).
3. Finally, an ex post assessment is undertaken to develop fragility curves for roads and bridges using post-event survey data associated with the 2011 'Tohoku' earthquake tsunami (Chapter 3).

These three parts of this risk analysis are ultimately used to model the impacts on Christchurch city infrastructure of a hypothetical tsunami scenario (Chapter 4), based on methods developed in Chapter 2, and implementing the impact assessment process presented in *Figure 1.2*.

The risk evaluation stage of the risk management framework is used in the context of this thesis to prioritise areas that would benefit the most from risk reduction strategies (Chapter 4). Response and mitigation options are presented for tsunami impacts on infrastructure (Chapter 4).

Having completed the risk management process, recommendations are given for the risk management of tsunami on Christchurch city infrastructure, as well as potential future research which addresses the post assessment monitoring and review stage of the risk management process (Chapter 5).

Chapter 2

Infrastructure Vulnerability and Impact Assessment Methodology

2.1 Introduction

The objective of this chapter is a credible and realistic tsunami impact model for Christchurch city infrastructure. This is achieved by firstly reviewing relevant literature related to infrastructure tsunami vulnerability. This builds on the review of tsunami damage styles and Christchurch tsunami hazard from Chapter 1. The objective of this review is to identify the impacts on infrastructure following significant tsunami recorded in international case studies, as well as identifying methods for modelling tsunami impacts on infrastructure, including the availability and selection of appropriate model input parameters. There is currently little knowledge of this, and so the present research is a new contribution. To address a lack of model parameters identified in the literature review, methodology for developing a tsunami damage matrix for infrastructure is presented, to be used as vulnerability metrics within the greater objective of developing tsunami impact models for Christchurch city infrastructure.

The overall chapter structure is presented in Figure 2.1 where it can be seen that the review of tsunami impact assessment methods (Section 2.2) are used to inform the methodology of a tsunami impact assessment on Christchurch city infrastructure (Section 2.4). The gaps identified in the review of tsunami impact assessment literature (Section 2.2) are used to identify a need for the development of a tsunami damage matrix for infrastructure (Section 2.3), as well as identifying associated gaps in the research methodology of this thesis (Section 2.5.1). The review of vulnerability demand parameters in tsunami impact assessments (Section 2.2.1) and the results of the tsunami damage matrix (Section 2.3.2) are used to inform vulnerability metric application when implementing an impact assessment methodology for tsunami impacts on Christchurch city infrastructure (Section 2.4.1), the results of which are presented in (Chapter 4).

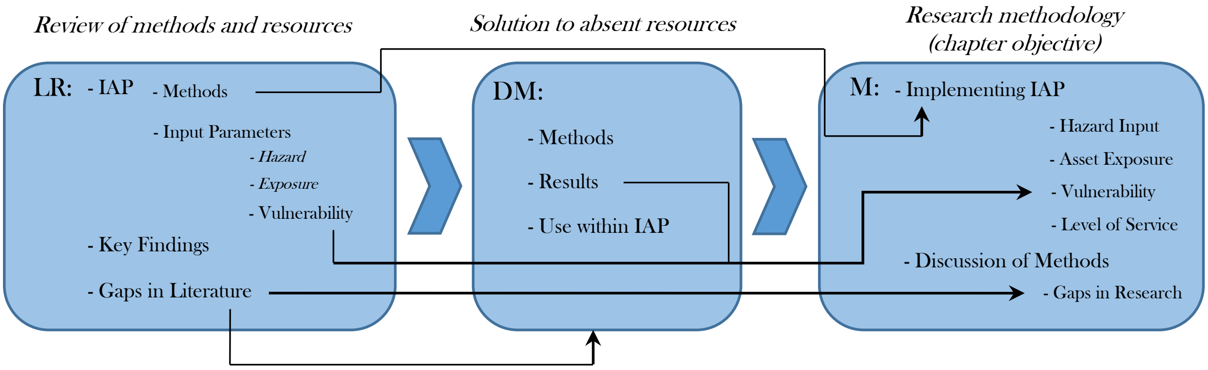

Figure 2.1: Chapter 2 structure. LR = tsunami impact assessment literature review; DM = tsunami damage matrix; M = tsunami impact assessment methods; IAP = impact assessment process. Note that hazard and exposure are not the focus of the impact assessment process input parameters review due to prior availability

2.2 Review of Tsunami Impact Assessment Literature

The objective of this section is to inform a tsunami impact assessment on Christchurch city infrastructure. The first step towards this is to review previous impact assessments, both empirical and theoretical, to constrain appropriate methodology. The remainder of this review focuses on identifying the availability, types and treatment of infrastructure tsunami vulnerability metrics, to implement within a tsunami impact model of Christchurch city infrastructure.

Prior to an actual tsunami event, it is difficult to determine the distribution and extent of infrastructure damage. However, systematically assessing how infrastructure components and networks were impacted, previous tsunami events can be used to inform how infrastructure may be impacted by future tsunami events.

The use of local asset vulnerability data is always preferential in an impact assessment (Power 2013; Horspool & Fraser 2015; NIWA 2014). However, a lack of damaging tsunami in New Zealand's recent history, as outlined in Chapter 1, means there are no local data to draw upon for an accurate infrastructure impact assessment. International case studies are therefore a useful tool to establishing impact model processes and parameters for tsunami (NIWA 2014). The most common impact assessment methodology is an empirical approach such as a post-event survey (Bell et al. 2005; Chandrasekar & Ramesh 2007; Ghobarah et al. 2006; Kim et al. 2014). As identified in Chapter 1, post–event surveys involve recording damage observations and hazard magnitude indicators in the field to assess the vulnerability of affected elements. They are used for ex post impact assessments to either inform response and recovery efforts or to validate previous ex ante assessments (Okal et al. 2010; Fritz et al. 2011; Bell et al. 2005; Power 2013; Horspool & Fraser 2015). They can also be used to develop fragility metrics for future ex ante risk or impact assessments. While the impacts in these events are obvious, the source of the damage is often uncertain, or harder to determine, such as hydrodynamic forces, inundation depth and flow velocity (Koshimura, Oie, et al. 2009). For this reason an analytical approach is often taken to address these uncertainties (Prasetya et al. 2012; Lane et al. 2014; NIWA 2014; Centre for Advanced Engineering 1997).

As recommended by Koshimura et al. (2009), statistical analysis is the best approach to widespread tsunami impact modelling given the often limited resource and time post-event. A less common approach for tsunami impact assessments is an experimental one, involving the recording of asset performances under various simulated conditions based on controlled tsunami forces (e.g. Chen & Melville 2015). In the absence of data, or to supplement what is available, expert opinion can be used as a justifiable impact assessment (e.g. Centre for Advanced Engineering 1997; Horspool & Fraser 2015). Subjective assumptions for analytical and experimental methods are also based on expert opinion.

As outlined in Chapter 1, various demand parameters are required for an impact assessment. Hazard metrics are already available for Christchurch tsunami hazards, as outlined in appendix 7.1. Asset exposure and vulnerability are not yet constrained for Christchurch city infrastructure, however they can both be analysed qualitatively, semi-quantitatively or quantitatively in order to constrain measures for the input of an impact assessment on infrastructure. All of these have the potential to produce outputs constraining impacts on infrastructure, but each has varying advantages and disadvantages, as identified in Chapter 1. Qualitative tsunami impact assessments can be conducted using sparse data and are often not labour-intensive, these include damage matrices and expert judgement. They are however commonly biased, low-resolution and ill-purposed for subsequent risk treatment strategies, such as cost-benefit studies (Reese n.d.; Power

2013). Conversely, quantitative tsunami impact assessments require extensive empirical data inputs and are often labour-intensive. They will however result in modelled impacts which are comparable, high resolution, consistent and unbiased (Reese n.d.; Power 2013). An appropriate tsunami impact assessment methodology therefore depends on two things: the specific model requirements; and the availability of demand parameters. Both of these influence the reliability and accuracy of the given impact assessment's outputs (i.e. damage to infrastructure).

2.2.1 Tsunami Vulnerability Parameters

Tsunami vulnerability is defined as the structural damage probability with particular regard to the hydrodynamic features (hazard) of a tsunami. These hazard metrics commonly include inundation depth, flow velocity and hydrodynamic force (Koshimura et al. 2009; Akiyama et al. 2013; GNS & NIWA 2015). In principle, the development of tsunami vulnerability metrics require that hazard data and damage statistics be used in parallel to produce fragility functions, as defined in Chapter 1. Fragility functions related to tsunami damage tend to be empirical curves determined from remote sensing, numerical modelling, and field surveys. These typically relate to a single tsunami event meaning the fragility curve will be specific to the characteristics of that tsunami and the local asset standards (e.g. construction standards). This means individual fragility functions do not provide a universal measure of tsunami impact or damage (Akiyama et al. 2013; Koshimura et al. 2009). Current scientific literature focuses heavily on vulnerability metrics for tsunami impacts to buildings and casualty estimations. Few examples of tsunami fragility functions for infrastructural assets exist. The available data are as summarised in Table 2.1.

Table 2.1: Summary of fragility functions for tsunami impacted infrastructure

Infrastructure Asset	Data type	Attributes	Hazard Demand Parameter	Data source	Tsunami Event	Reference
Transport						
Bridges	Fragility curves	Construction type, 3 damage states	Inundation Depth (above base of deck)	Post-event damage survey	Indian Ocean, 2004	*(Shoji & Moriyama 2007; Horspool & Fraser 2015)*
	Damage curve	3 damage states	Inundation	Post-event damage survey	Tohoku, 2011	*(Eguchi et al. 2013)*
	Fragility curve	3 Damage states	Inundation depth (above base of deck)	Damage Simulations	Tohoku, 2011	*(Akiyama et al. 2013)*
Water						
Wastewater Facility Buildings	Fragility curve	1 Damage state	Inundation depth	Post-event damage survey	Tohoku, 2011	*(Horspool & Fraser 2015)*
	Fragility curve	2 damage states	Inundation depth	Post-event damage survey	Tohoku, 2011	*(Eguchi et al. 2013)*
Energy						
Utility Poles	Fragility curves	Construction type, 2 damage states	Inundation depth (as a ratio to pole height)	Expert judgement	Multiple	*(Horspool & Fraser 2015)*
Substations	Fragility curves	Indoor/outdoor components, 3 damage states	Inundation depth	Expert judgement	Multiple	*(Horspool & Fraser 2015)*
Fuel Storage Tanks	Fragility curve	Probability of damage	Inundation depth	Post-event damage survey	Tohoku, 2011	*(Hatayama 2014)*

Not all of the available infrastructure vulnerability metrics would apply to a New Zealand setting. The most common hazard parameter for empirical fragility functions (of buildings) is inundation depth (Reese et al. 2011; Suppasri, et al. 2013). This is a result of the comparatively easy identification of inundation depth markers (e.g. Figure 1.5) during post-event surveys (e.g. Goff et al. 2006). However, this is not always the most significant cause of damage - velocity and debris impacts can play as important a role as inundation depth in the spatial distribution of damage during a tsunami, as reviewed from relevant literature below.

2.2.1.1 Velocity

Koshimura et al. (2009) recommend not to use velocity in the application of fragility functions, but instead to use inundation depth. This is due to velocity models being significantly dependant on grid resolution and topography data used. However, King & Bell (2006) argue that inundation is also sensitive to inaccuracies in topographic data as well as the assumption of static topography in modelling. Velocity can be difficult to quantify ex post, and difficult to measure during a tsunami event. However a study by Fritz et al. (2012) measures flow velocity from the 2011 'Tohoku' earthquake using survivor videos of the event and LIDAR techniques. They determined that flow velocities reached 11 m/s at the research location. Techniques like the one presented by Fritz et al. (2012) could be used in future ex post tsunami impact assessments to develop fragility functions with a flow velocity hazard intensity metric, thereby increasing the resolution and realism of outputs.

2.2.1.2 Debris Impacts

Debris impacts are not commonly used as a vulnerability metric. The one example of reviewed literature using debris impacts as a measure of fragility was Reese et al. (2011). However, these were designed based on buildings in Banda Aceh. The probability of exceeding a given damage state for a given water depth is less for a shielded structure (e.g. behind a reinforced masonry building) than for a non-shielded structure. The effects of debris on asset vulnerability had not been quantitatively examined prior to Reese et al. (2011), due to the complex site-specific and event-specific nature of the associated damage.

Vulnerability metrics which do not consider debris, while inaccurate, are still practical for the likes of residential areas. Reese et al. (2011) use a classification system of 'shielded' or 'exposed' based upon the presence of another structure or significant topographic feature on the sea-facing side of the given asset. This measure of shielding is used for its simplicity and Reese et al. (2011) recognise that it would not accurately portray damage associated with a flow direction oblique to the shore line or retreating flows. The methods used by Reese et al. (2011) are simple but largely inaccurate, as the authors acknowledge. The inclusion of methods for debris site assessment and dispersal by Naito et al. (2014) could be used in conjunction, to determine with more accuracy the shielded or exposed status of a structure or network, in order to apply a level of vulnerability. These methods are comparatively complex but far more accurate. An issue with the methods used by Naito et al. (2014) however, is that the specific debris source will vary on a day-to-day and even hour-to-hour basis with regards to mobile objects (e.g. vehicles, containers and vessels). Only debris sourced from static structures (e.g. buildings) would be spatially-temporally fixed.

Naito et al. (2014) examined four regions of Japan, following the 2011 'Tohoku' earthquake tsunami, classifying debris objects into three categories (Table 2.2) in order to calculate their potential impact forces (e.g. Table 2.3). Naito et al. (2014) specifies that this can be estimated by:

$$F = r \cdot U_{max}\sqrt{k \cdot m_d(1 + c)}$$

Where F = impact forces in kilonewtons (kN); r = the importance coefficient for a given risk category; U_{max} = maximum flow velocity carrying the debris; m_d = mass of the debris; k = effective stiffness of the debris; and c = hydrodynamic mass coefficient. Note that this equation requires knowledge of an object's mass and stiffness value.

It must be assumed that this measure of impact force is proportional to the likelihood of the given object striking a structural component (Figure 2.2). The assumption is made that the debris will disperse from its origin in a direction normal to the coast with variation. The origin is determined by the geometric centre of the debris object's original site. Because of variations in onshore flow conditions, a spread of dispersal of +/- 22.5 degrees from shore normal is assumed.

Table 2.2: Classification of tsunami debris (modified from Naito et al. 2014)

Debris Category	***Grouping definition***	***Examples***
Small Debris	*Suspended objects that are not large enough to impart significant force on impact*	*Household items, foliage, detached pieces of wooden structures.*
Moderate Debris	*Objects can result in localized impact as well as damming on structures and would represent a typical force demand*	*Wooden poles and trees, empty containers and trailers, concrete and stone objects, vehicles, fibreglass vessels,*
Large Debris	*Large debris objects can impart excessive force on impact and produce significant damage to an engineered structure*	*Loaded containers and trailers, concrete and stone structures, wooden structures, large steel vessels.*

Table 2.3: Examples of Estimated Debris Generated impact Forces (Naito et al. 2014).

Debris types	***Debris size***	***Stiffness*** (kN/mm^2)	***Mass*** *(kg)*	***Impact forces*** (kN)
Wood pole	Moderate	2.4	450	131
Vehicle	Moderate	1.0	1,000	133
Container (empty)	Moderate	85	2,200	1,770
Container (full)	Large	85	30,000	6,390
Barge	Large	60	181,000	13,180

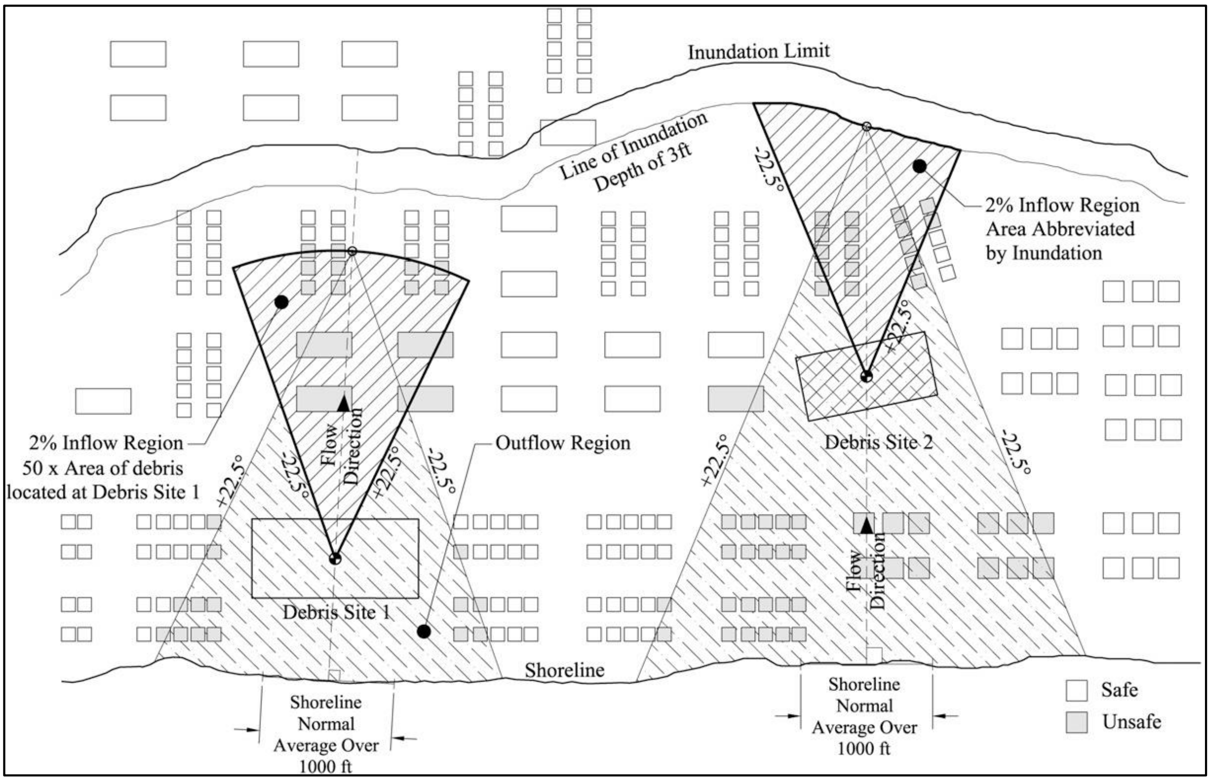

Figure 2.2: Debris dispersal calculation (Naito et al. 2014)

2.2.1.3 Inundation Depth

King & Bell (2006); Marchand et al. (2009); Mas et al. (2012); Graf et al. (2014) and Eguchi et al. (2013) all determine that tsunami damage is very sensitive to inundation depth, with particular regard to the floor heights of buildings. This makes them the most frequent hazard intensity measure for tsunami fragility functions (see Table 2.1).

Limited damage tends to occur if inundation remains below floor height, with moderate to significant damage occurring from depths just above floor height upwards. This is of particular relevance to infrastructure components housed in buildings (such as pump houses, substations, etc.) more so than to the networks themselves. This is supposedly a threshold where any degree of inundation to internal structures, components and equipment, will result in the need for almost complete replacement (King & Bell 2006). Damage state (level of damage) classes with such sensitivity rely on the precision of topography and inundation models, if an impact assessment is to produce realistic outputs. It also means that inundation depth, and by association damage, is very dependent of the performance of flood and coastal protective structures (sea walls, stop banks etc.). This is an issue because as these structures become damaged or washed away in a tsunami, uninhibited flows occur where they would have otherwise not (e.g. as a coastal dune is eroded, tsunami waters are progressively less constrained behind it). This can be difficult to predict accurately in tsunami hazard modelling, most of which use static topography (King & Bell 2006).

Among coastal transportation networks, bridges are often the most vulnerable structures to tsunami damage given the increase in flow velocities along channels they cross. There is also often a lack of any obstructions to shield debris or slow the incoming waves (Akiyama et al. 2013). Of the limited examples of published infrastructure fragility curves, the majority are devoted to bridges and use inundation depth as a hazard intensity measure (Akiyama et al. 2013; Eguchi et al. 2013; Marchand et al. 2009; NIWA 2014; Horspool & Fraser 2015). Eguchi et al. (2013) and Akiyama et al. (2013) have produced the most bridge fragility functions, all of which are based on Japanese structures. This makes them applicable to New Zealand construction standards, which are similar. Akiyama et al. (2013) present analytical fragility curves for three failure modes: buoyancy force, wave force, and shear failure of bridge piers. The damage states reported are 'slight/none', 'moderate', and 'extensive/collapse'. NIWA (2014) states that these are too complex for integration into an impact model and that a tsunami inundation depth parameter would need to be applied to make this more functional. Horspool & Fraser (2015) use data from Shoji & Moriyama (2007) to develop fragility curves for bridges of three construction types (Figure 2.3). Although they would provide a more accurate distribution of damage, based on the resistance to impacts of various construction types, they are based on Indonesian and Sri Lankan standards, which are not akin to New Zealand bridges. Note that for PC (precast concrete) and steel bridges there were not enough data at Damage State 2 to include in the analysis. The hazard intensity measure for these fragility curves is inundation depth with respect to height above the base of bridge decks.

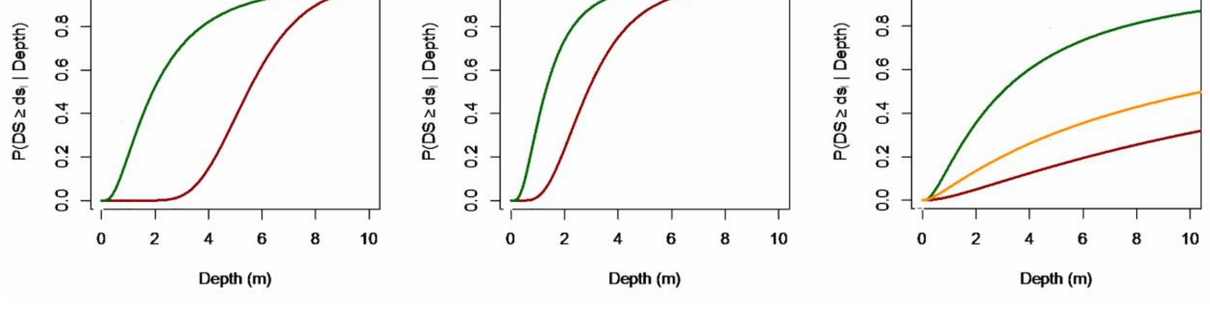

Figure 2.3: Bridge fragility curves, modified from Horspool & Fraser (2015)

Eguchi et al. (2013) have also produced fragility curves for bridges, using data from 177 damaged bridges in two Japanese prefectures following the 2011 'Tohoku' earthquake tsunami. The dataset contains only bridges that suffered some damage. There is consequently substantial non-coverage of data which are therefore unrepresentative of all Japanese structures affected by the tsunami. NIWA (2014) suggests the fragility functions associated with these data be used with caution because of these limitations.

Fragility curves have also been developed for road tsunami vulnerability. Marchand et al. (2009) developed fragility curves for three types of roads (national, city and neighbourhood) for the 2004 'Indian Ocean' tsunami in Banda Aceh. These use inundation depth as a hazard intensity measure due to data limitations for other metrics. It is noted that the relationship between road damage and inundation depth is weak, especially by comparison with housing. It is suggested that this may be explained by damage to roads not occurring from the incoming wave but from erosion during receding floodwaters. It is also suggested that better variables would be the use of road orientation to flow direction or road elevation above ground level. Marchand et al. (2009) indicate that damage probability for any types of road below 1 m inundation depth is a linear function of depth, whereas damage above this threshold will always have a probability of 1.0. Similarly for bridges, the transition from a linear function of depth to 100% damage probability is aproximately 2 m above deck height. This sensitivity may be representative of Indonesian road construction but is not so clear cut in literature relating to the likes of Japanese roads (Akiyama et al. 2013; Eguchi et al. 2013), which share similar construction standards to their New Zealand counterparts.

One other infrastructural sector with available fragility curves is electricity. Horspool & Fraser (2015) have developed these for substations and utility poles (timber & concrete) based on expert-judgement, given the lack of empirical data. For utility poles fragility is defined as a function of inundation depth to pole height. Substations are split into interior and exterior facilities.

2.2.2 Discussion of Impact Assessment Literature

The following is a discussion, proceeding the review of relevant literature, on what has been identified for an effective tsunami impact assessment. Also discussed is whether an impact assessment process can be implemented to constrain the tsunami impacts on Christchurch city infrastructure.

The literature has identified that an effective tsunami impact assessment on infrastructure requires the use of hazard and exposure measures to inform a relevant vulnerability metric, of which fragility curves, with an inundation depth hazard intensity measure, have been identified as the most applicable option. The most reliable fragility functions are those which use quantitative data with large quantities of damage and/or hazard observations recorded. Qualitative data can however be used in its absence for the development of tsunami vulnerability metrics, including damage matrices and expert judgement. Locally sourced vulnerability data was identified as being the most applicable for tsunami impact model demand parameters, however in the absence of availability, comparable data can be implored. In the context of this research, Japanese sourced data has been identified as the most comparable for New Zealand infrastructure tsunami impact assessments. An absence of applicable tsunami vulnerability metrics has also been identified, which will be a limiting factor in implementing a tsunami impact assessment process on Christchurch city infrastructure.

A gap has been identified in the availability of applicable fragility functions for infrastructure vulnerability to tsunami in New Zealand. It has also been identified through their absence, that there are no previous examples of a comprehensive infrastructure tsunami impact assessment from which to draw recommendations**.** In order to address most of the shortcomings in the availability of resources, a vulnerability metric will need to be developed for each infrastructural asset that is otherwise lacking one. Available quantitative fragility functions only apply to bridge damage and these data are stated as not being akin to New Zealand infrastructural standards, and potentially unreliable (GNS & NIWA 2015). The ability to develop relevant input parameters is apparent, however the creation of these would be out of the scope of this project. The inclusion of all vulnerability demand parameters, including inundation, velocity and debris impacts, would allow for the development of the most credible and realistic impact model however the literature review has highlighted the large scope of work that would be involved given the lack of available data.

In order to apply a debris impacts vulnerability metric similar to that described by Reese et al. (2011), sections of each infrastructural network would have to be classified by debris exposure potential and then an appropriate weighting system applied. This would be both subjective and labour-intensive. The methods presented by Naito et al. (2014) could be used to classify potential debris types, quantify the debris potential for a given site and then translate the debris and debris potential to impact loads on structures. Although there is a focus on building impacts, as with much of the tsunami literature, these methods could be easily applied to engineered infrastructure including bridges, utility poles, and substations. This methodology does not include debris impacts for surface-level or below-ground infrastructure, from the dragging effects of debris entrained in the water column.

Reese et al. (2011) acknowledge that without eye-witness reports it is often impossible to know which debris objects relate to specific structural damage or collapse post-event. This information would be required to produce some kind of debris-based fragility function. Another concern is that the inclusion of a debris dispersion model would require the identification of every possible debris source. Vehicles, wood debris, rubble, trailers, and building components are examples of debris types of which the origin is difficult to define prior to the occurrence of the tsunami. Given the time involved in applying a debris impact weighting system, plus the fact that inundation and velocity models already exist for Christchurch, it will be appropriate to omit debris impacts as a direct vulnerability metric for this project.

Koshimura et al. (2009) recommend not to use velocity in the application of fragility functions, but instead to use inundation depth. This is due to velocity models being significantly dependent on the grid resolution and topography data used. However the latest tsunami velocity model for Christchurch (Lane et al. 2012), as with the inundation model, has high grid and topographic resolution. Nevertheless, given the lack of available velocity-related resources, for the purposes of this project, it appears the most logical action will be to limit the vulnerability demand parameters to inundation depth. There are significantly more inundation-depth-related resources relevant to a New Zealand setting (Horspool & Fraser 2015) and the development of new resources will be less labour-intensive if focused on this vulnerability metric.

An impact assessment process has been identified as an appropriate method by which to model tsunami impacts on Christchurch city infrastructure. However, quantitative tsunami vulnerability input parameters are largely unavailable for infrastructure. This could be addressed in one of two ways: by using available quantitative data (i.e. from 'Tohoku' earthquake tsunami, Japan), to develop fragility functions; or by developing a qualitative vulnerability metric for each infrastructural asset. As alluded to in the above literature review, the 'Tohoku' data is robust enough for the use of road and bridge vulnerability metric development. Given this, the development of these may be within the scope of the present research. For infrastructural assets other than roads and bridges, a qualitative tsunami damage matrix could be developed to provide a vulnerability metric based on an inundation depth hazard intensity measure. Note that qualitative fragility curves are available for electricity assets and fuel storage tanks (Horspool & Fraser 2015; Hatayama 2014) which would provide a higher resolution vulnerability input than a damage matrix.

2.3 Tsunami Damage Matrix

A tsunami impact assessment for Christchurch city infrastructure requires a measure of vulnerability for each asset. The above literature review has identified a gap in the availability of quantitative damage data for infrastructure and therefore a lack of available fragility functions, and an inability to derive them, due to the lack of data. Fragility functions could presumably be developed for most assets given enough time and resources (experimentally or by post-event surveys of future events), but within the scope of this research project the most appropriate course of action will be to use a qualitative solution. Power (2013) states that for ex ante analyses (such as that in the present research), risk matrices provide a systematic method for assigning a hazard intensity measure to a level of damage. This approach makes it possible to link the impact results back to the risk management framework (Figure 1.1) to ultimately reduce tsunami impacts and therefore risk. This section presents the methods specific to developing a tsunami damage matrix for the purpose of a vulnerability metric within the greater objective of developing a tsunami impact assessment of Christchurch city infrastructure (see Figure 2.1).

2.3.1 Damage Matrix Methodology

Using a similar method to Wilson et al. (2009) and Daly & Johnston (2015), damage probabilities are assigned for each infrastructural asset based on hazard intensity categories. For tsunami impacts to infrastructure inundation depth will be used as the hazard metric, as discussed in the literature review, and three distinctive depth categories have been identified: <0.5 m, 0.5-2 m and >2 m (e.g. Table 2.4). These were selected for the following reasons:

Two meters of inundation has been identified as a key damage threshold. This is often the depth of water required to potentially start mobilising large debris as well as beginning to exert significant hydrodynamic forces. It is also a depth at which all assets are likely to experience some degree of potential damage (King & Bell 2006). 0.5 m – 2 m inundation depths are where the potential for damage to most assets begins to occur, as medium debris objects are beginning to mobilise and the flow speeds are enough to begin exerting hydrodynamic forces on structures. <0.5 m of inundation is a key threshold to pinpoint assets which are the most susceptible to tsunami inundation, because at this depth only small debris objects are able to mobilise and flow speeds are likely to only potentially affect weak or buoyant objects. The main cause of damage within this depth bin is likely silt deposition and water damage to low lying assets.

Table 2.4: Example of tsunami damage matrix design and inputs. Completed tsunami damage matrix found in Appendix 7.3

Infrastructural Asset	*Flow Depth < 0.5m*		*Flow Depth 0.5m – 2m*		*Flow Depth >2m*		*Data Quality*
	Probability of Damage	*Damage Type*	*Probability of Damage*	*Damage Type*	*Probability of Damage*	*Damage Type*	
e.g. road pavement	*e.g. low*	*e.g. siltation*	*e.g. medium*	*e.g. scour*	*e.g. high*	*e.g. washout*	*e.g. high*

The content of the damage matrix will be developed through a subsequent review of damage specific observational and theoretical recordings. Quality of data will also be recorded in the damage matrix, indicating the accuracy of assigned likelihoods. A low data quality value would indicate a low volume of qualitative data or a purely subjective likelihood assignment. A high data quality value would indicate a high volume of qualitative data or the use of quantitative observations.

2.3.2 Damage Matrix Results

The damage matrix constrains a probability of damage occurring and a description of the potential damage types, for three inundation depth categories. It equates to a summary of all relevant and available literature containing a degree of infrastructural asset damage and/or hazard intensity relationship. Appendix 7.3 displays the completed tsunami damage matrix.

Although initially developed from current scientific literature, the tsunami damage matrix (Appendix 7.3) has been updated to include observations made during a post-event field survey following the 2015 ‘Illapel’ earthquake tsunami in Chile. This was carried out in the city of Coquimbo, which experienced inundation up to 600 m inland, with inundation depths of up to

7 m at the coast (Gaurdian News and Media Limited 2015). The census style survey was run by GNS Science and empirical data were collected for over 3,000 transport, energy and water infrastructure assets as well as over 600 inundation depth indicators across the inundation zone. The damage data collected will eventually provide valuable fragility curves, but these are not within the scope of this research. The present models do not incorporate any of the survey data collected, however the damage matrix (Appendix 7.3) incorporates relevant and specific observations from the field. General observations were used to calibrate the tsunami damage matrix, while specific damage observations were used to update existing damage descriptions and assigned likelihoods of damage (Appendix 7.4). This adheres to the review and monitoring stage of the risk management framework (Figure 1.1).

The tsunami damage matrix appears to be the first of its kind for assessing tsunami impacts to infrastructure. Its applications, irrespective of an impact assessment, includes providing a comprehensive 'look up' resource for infrastructure asset managers, emergency managers and planners to identify key damage styles for specific assets at varying hazard intensities, which adheres to the risk treatment stage of the risk management framework. As with most qualitative analyses, this damage matrix is subjective and relatively low-resolution. Nevertheless for the purpose of an infrastructure impact assessment for Christchurch city, it provides a vulnerability metric to use, in the absence of fragility curves, within a tsunami impact assessment process (Figure 1.2) as described in more detail below. It should not however be used to replace fragility curves, if available.

2.4 Tsunami Impact Assessment Methodology

The objective of this section is to develop methods to complete a tsunami impact assessment for Christchurch city infrastructure. This builds on previous sections of Chapters 1 and 2 by putting an impact assessment process into practice by implementing relevant and applicable data including a qualitative tsunami damage matrix and developed fragility curves (Chapter 3).

2.4.1 Applying the Impact Assessment Process

The impact assessment process involves first constraining the hazard (hazard scenario model) and the selection of an appropriate hazard metric (i.e. inundation depth). Asset exposure is then determined by spatially assigning inundation depths to each asset. Next an applicable vulnerability metric is selected based on the most relevant available method. Since fragility functions are unavailable for many infrastructural assets (Section 2.2), a damage matrix (Appendix 7.3) was developed based upon scientific literature and post-event tsunami survey observations, to define asset vulnerability to inundation. To determine the impacts on a network, the chosen vulnerability metric (fragility curve or damage matrix) is used to assign a probability of damage based on inundation depth and construction type (if available).

The impact assessment process involves the selection of a variety of different parameters as explained below and outlined in Figure 1.2.

2.4.2 Selecting Hazard Input

Based on the literature review in Section 2.2, inundation depth will be used as the hazard metric for modelling the impacts on Christchurch city infrastructure. As stated, this is the current standard for tsunami impact modelling and has the most available resources (Horspool & Fraser 2015). The impact models will therefore be deterministic as they are based on a single hazard scenario. The methods used for this tsunami impact assessment could be applied to any hazard model, limited only by the availability of relevant input parameters. Network exposures can be determined by spatially assigning inundation depths to the available assets.

2.4.3 Availability of Asset Attributes

Spatially constrained asset data is required to determine infrastructure exposure to modelled inundation depth. For quantitative modelling, asset attribute data is also required to distinguish different levels of fragility based upon various qualities of each asset. This provides a higher resolution impact assessment, but again is determined by the availability of relevant vulnerability metrics.

Table 2.5 lists the assets with available data following an exhaustive search from various public and commercial sources. Most infrastructural sectors are represented, the notable exceptions being in the electricity and telecommunications sectors which are not publicly accessible. The methodology presented for this impact assessment can be used to include more assets if they become available in the future. Exposure to tsunami hazard is determined by assigning inundation depths. Based on this exposure assignment, a vulnerability metric can then be applied.

Table 2.5: Infrastructure asset data sources and relevant attributes for tsunami impact assessment

Infrastructure Asset	Relevant Attributes	Data Source
Wharves	Width, length	*Satellite Imagery*
Fuel Storage Tanks	Diameter	*OpenStreetMap contributors 2015, Satellite Imagery*
Roads	Pavement material, surface depth, surface date, surface condition, length, span, use type	*Stronger Christchurch Infrastructure Rebuild Team, OpenStreetMap contributors 2015*
Rail	Track type, use type, vehicle type	*Koordinates contributers 2015*
Wastewater Pipes	Length	*Koordinates contributers 2015*
Wastewater Pump Stations	None	*Satellite Imagery, field Survey*
Potable Water Pipes	Length	*Koordinates contributers 2015*
Stormwater Pipes	Length	*Koordinates contributers 2015*
Open Drains	Length	*Koordinates contributers 2015*
Bridges	Structural condition, construction type, construction year, use type, width, span, length, heritage status,	*Stronger Christchurch Infrastructure Rebuild Team*
Cellular Towers	Frequency, power, provider	*Koordinates contributers 2015*

2.4.4 Vulnerability Metrics

The review of infrastructure impact assessment literature determined that empirical fragility curves were the most appropriate vulnerability metric to use for tsunami modelling. There are two main vulnerability methods that can be applied to infrastructure tsunami damage probability models; qualitative (damage matrix) or quantitative (empirical fragility curves). There is also the option to use existing, or future, post-event tsunami survey data to produce new and potentially more relevant fragility functions. Figure 4.2 illustrates the decision process used to select the most appropriate data for modelling tsunami impacts on infrastructure given the lack of available data determined from Section 2.2. The impact modelling process will vary depending on the vulnerability method selected. Table 2.6 indicates the highest resolution vulnerability metric for each available infrastructure asset. Note that the fragility curves being used for roads and bridges are to be covered in Chapter 3.

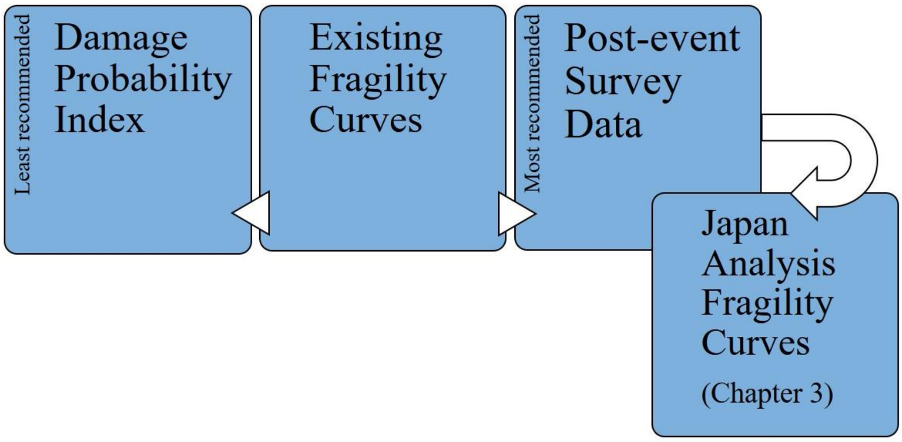

Figure 2.4: Decision process for selecting an appropriate vulnerability metric for modelling tsunami impact on infrastructure. If empirical data are unavailable then the damage matrix will be used to determine damage probabilities. If more applicable quantitative data are/become available, these should be used to create new empirical fragility curves for assets to determine damage state occurrence probabilities (e.g. Japan roads damage analysis, as outlined in Chapter 3)

Table 2.6: Most applicable vulnerability metrics for each available Christchurch city infrastructure asset

Infrastructure Asset	Highest Resolution Vulnerability Metric	Data type	Data Source
Wharves	Damage Matrix	Qualitative	Chapter 2
Fuel Storage Tanks	Damage Curve	Semi quantitative	(Hatayama 2014)
Roads (Generic)	Fragility Curve	Quantitative	Chapter 3, Horspool & Fraser 2015
Roads (Use Type)	Fragility Curves	Quantitative	Chapter 3
Bridges	Damage Matrix	Qualitative	Chapter 3, Horspool & Fraser 2015
Rail	Damage Matrix	Qualitative	Chapter 2
Wastewater Pipes	Damage Matrix	Qualitative	Chapter 2
Wastewater Pump Stations	Damage Matrix	Qualitative	Chapter 2
Potable Water Pipes	Damage Matrix	Qualitative	Chapter 2
Stormwater Pipes	Damage Matrix	Qualitative	Chapter 2
Open Drains	Damage Matrix	Qualitative	Chapter 2
Cellular Towers	Damage Matrix	Qualitative	Chapter 2
Utility Poles	Fragility Curves	Expert judgement	Horspool & Fraser 2015
Substations	Fragility Curves	Expert judgement	Horspool & Fraser 2015

2.4.4.1 Qualitative Damage Matrix Input

As shown in Figure 4.2, a damage matrix approach should only be used in the absence of relevant fragility curves. If that is the case then impact assessment models will be run by determining an asset's level of exposure to the tsunami hazard (inundation depth). Then by assigning each asset into inundation depth bins, a vulnerability metric (probability of damage) can be applied. The way that qualitative damage matrix data can be applied is by grouping the exposed assets into the three associated depth bins (<0.5 m, 0.5-2 m, >2 m). This then allows a likelihood of damage to be applied to each asset's inundation grouping. Given what the damage matrix is representing, only a probability of damage is expressed using this method. This is because the damage matrix does not constrain a level of damage (i.e. damage state).

The main factors limiting this approach include:

- Qualitative data inputs
- Broad inundation groupings
- Subjective damage probabilities
- Level of damage not expressed

2.4.4.2 Quantitative Fragility Functions

The methods for applying fragility curves to a tsunami impact assessment are similar to those described above, only differing in the level of complexity and output resolution. The asset data are first categorised by the applicable attribute being tested for vulnerability (e.g. construction type, road use etc.). The use of fragility curves allows depth bins of 0.5 m to be used which maximises the effectiveness of the high resolution tsunami inundation model. The assets will be grouped into these depth bins and for depths below 1 m, 0.25 m depth bins were used to increase resolution (e.g. 0.25 m – 0.5 m depth bin). Then using the vulnerability metric, a probability of damage is assigned to each depth bin, for each attribute category, and for each applicable damage state (e.g. DS1, DS2, and DS3). This method provides outputs which are significantly more realistic then its qualitative counterpart. Results will be presented as a probability of an asset experiencing a given damage state.

2.4.4.3 Post-event Tsunami Survey Data

Another vulnerability metric option requires the same treatment as above, but involves developing new and potentially more relevant fragility curves following future tsunami events or experimental studies. This can also include the treatment of existing post-event tsunami survey data. One such example of this was referred to by various sources in Section 2.2 regarding the post-event tsunami damage data collected following the 2011 'Tohoku' earthquake tsunami. The analysis of these data are covered in Chapter 3.

2.4.5 Evaluating a Level of Service

Given the low resolution of qualitative modelling methods for many infrastructural assets, a level of service (service available or service not available) will be a useful additional method to present these data, especially for emergency managers and planners. Since the qualitative models are intrinsically low resolution this will be conducted at suburb scale and be based on the modelled results (probability of damage) as well as the above literature review and expert opinion (Snyder-Bishop, K, 2015, pers. comm., 17 November). Logical decisions will be made on the serviceability of each infrastructure network, as presented in completion in Appendix 7.5. The results will be limited by this subjective approach.

2.5 Discussion of Impact Assessment Methods

This chapter has determined the importance of quantitative vulnerability metrics for tsunami impacts on infrastructure, whilst also identifying the lack of applicable fragility functions available in current scientific literature. Previous studies that have assessed damage to infrastructure from tsunami have not always recorded all inundated assets, regardless of damage, which is a key barrier to the development of useful empirical fragility curves. The damage probability index is a low resolution option to supplement empirical data. The alternative is to not include assets lacking associated fragility curves until future tsunami, or experimental studies, allow the collection of damage data and the development of relevant vulnerability metrics (fragility curves). The findings from the review of literature indicate that it is important to consider the local context when selecting an appropriate vulnerability metric and to closely consider the shortcomings of using ones which may not be entirely applicable. This chapter has also identified that it is important to consider other hazard metrics in the impact assessment of infrastructure. These include flow speed, soil erosion and debris impacts. However, also highlighted is the scale of research that would be involved in this and that it may be very spatially and temporally specific.

This chapter has contributed to the risk management framework by providing a comprehensive damage matrix and outlining a methodology by which to model tsunami impacts on infrastructure given a low volume of resources currently available. These can be used together, or in isolation, to inform emergency managers and planners for the purpose of reducing tsunami impacts and therefore risk.

2.5.1 Gaps in Research

Gaps in the present research include:

- Impacts do not take into account flow speed or debris impacts, which are both significant causes of variation in tsunami damage distribution.
- Models based on the damage matrix do not provide a damage level metric (i.e. damage state)
- Models based on qualitative data represent a low resolution of damage distribution. They also do not take into account construction materials
- The method of serviceability designation is based on simple & broad decision making and the results may require a review by experts.
- Each infrastructure sector has many more assets in its network not available for this assessment, which could affect the level of serviceability depending on the damage to them.
- Does not consider the cascading impacts of network losses

2.6 Summary

A review of relevant literature has determined that the current state of science on the vulnerability of infrastructure to tsunami, is not sufficient enough to conduct a thorough impact assessment in isolation. A damage matrix has been developed to summarise qualitative data and post-event tsunami survey observations and substitute absent vulnerability metrics in a tsunami impact assessment, of which the methodology is subsequently presented. The results of this tsunami impact assessment will be used to determine an associated level of infrastructure service for each Christchurch city suburb.

Chapter 3

Quantitative Vulnerability Analysis of Japanese Roads to Tsunami Inundation

3.1 Introduction

The objective of this chapter is to develop quantitative tsunami inundation fragility curves for Japanese roads, to be used in tsunami impact modelling. This analysis is informed by the review of available fragility functions in Chapter 2, and uses data collected by post-event ground survey teams on damage from the 2011 'Tohoku' earthquake tsunami in Japan. Fragility curves have been developed in collaboration with GNS Science (Horspool & Fraser 2015).

Tsunami impact modelling can aid in tsunami mitigation and preparedness, however to do so a vulnerability metric is required. As determined in Chapter 2, fragility functions for tsunami impacts on infrastructure are not well constrained in the literature. Chapter 2 also provided a qualitative vulnerability method (tsunami damage matrix). However as discussed, this is a low resolution option and not applicable if quantitative fragility curves are available. Quantitative fragility functions provide the highest resolution vulnerability metric in a tsunami impact assessment and require detailed damage data collected during post-event field surveys (see Section 2.2).

Following the 2011 'Tohoku' earthquake tsunami, an analysis of impacted roads was carried out, using damage data from Miyagi and Iwate Prefectures in Japan. It has been recognised however that these data require further revisions in order to create a complete asset inventory for the development of fragility curves (Eguchi et al. 2013).

Road networks are one of the most vital lifelines for response and recovery actions following a tsunami disaster (Nakanishi et al. 2014; Horspool & Fraser 2015; Eguchi et al. 2013). First responders require access to impacted populations, and repair works to other lifelines can be delayed due to access constraints from damaged roads. Bridges are the most studied infrastructure asset in terms of tsunami impacts (e.g. Shoji & Moriyama 2007; Horspool & Fraser 2015; Kawashima & Buckle 2013). They are also often the most vulnerable part of a transportation network and can have other lifelines attached to them (water, electricity, telecommunications etc.) increasing their importance in a lifeline network. Bridges can thus be cascading weak points or 'hot spots' for those networks (Bell et al. 2005; Edwards 2006; Horspool & Fraser 2015).

The Mw 9.0 'Tohoku' earthquake in the Pacific Ocean, east of Japan, was the cause of the 2011 'Tohoku' earthquake tsunami disaster (Kazama & Noda 2012), (Figure 3.1). The maximum wave run up exceeded 30 m (MLIT 2012; Kazama & Noda 2012), resulting in more than 15,000 deaths and extensive damage to buildings and infrastructure in Japan (Eguchi et al. 2013; Graf et al. 2014). Many coastal bridges were damaged from lateral forces of the flow or by impacts from large objects, including boats and cars. Coastal road networks were damaged, or totally destroyed, either by debris impact or erosion of the substrate material (Eguchi et al. 2013; MLIT 2012; Horspool & Fraser 2015; Kawashima & Buckle 2013; Kazama & Noda 2012).

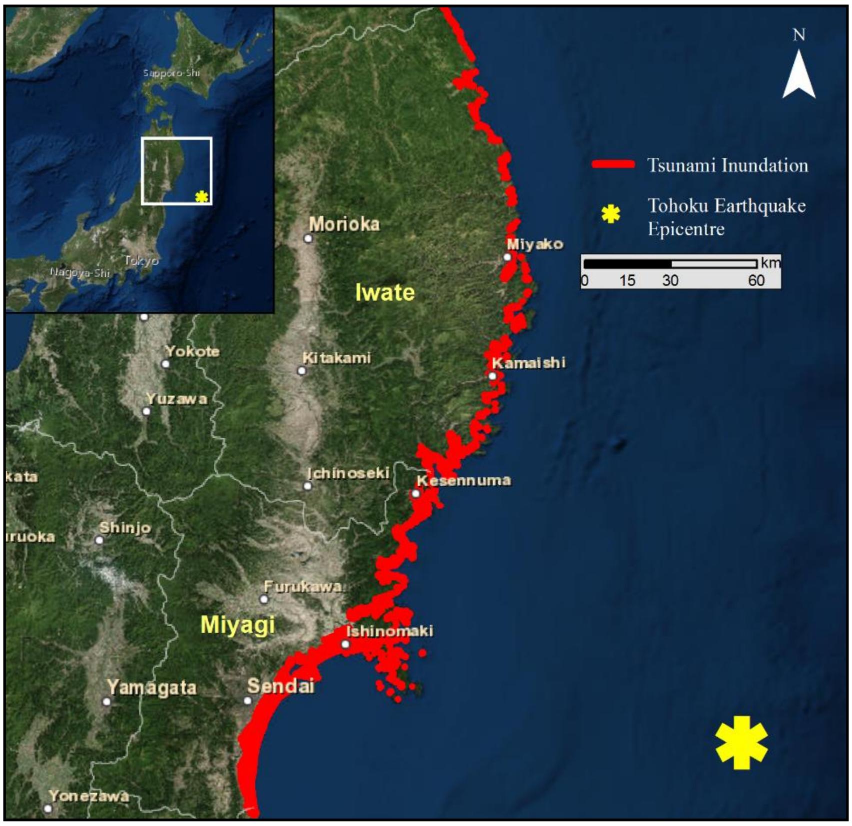

Figure 3.1: Inundation extent of the 2011 'Tohoku' earthquake tsunami along the coast of Miyagi and Iwate Prefectures, Japan (MLIT 2012)

3.2 Methods

The 'Tohoku' earthquake tsunami provided post-disaster survey teams with an extensive area from which to collect damage data on infrastructural assets. The data sets used for this analysis are the results of a comprehensive ground survey carried out in the days to weeks following the tsunami by the Japanese Government, City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT 2013). The data relevant to this analysis included detailed infrastructure damage summaries and local maximum tsunami flow depths for the inundation area within Miyagi and Iwate Prefectures (Figure 3.1), which were two of the regions most impacted (Eguchi et al. 2013; Horspool & Fraser 2015; MLIT 2012; Kazama & Noda 2012). The flow depth and road damage data were presented as GIS shapefiles (.shp) to GNS Science, which provided a basis for this analysis. The damage data sets were supplemented with a Japanese-to-English translated spreadsheet of instructions and explanations. Modelled maximum flow depth (m) data was available in 100 x 100 m grid cells, across the regions (Eguchi et al. 2013; MLIT 2012; Horspool & Fraser 2015). Table 3.1 outlines the data used in this analysis.

Table 3.1: Available data and properties for a quantitative vulnerability analysis of Japanese roads to tsunami

Data Type	Relevant Attributes	Format	Source
Roads	Road type, damage level, damage description	Shape-file	*(MLIT 2012; OpenStreetMap contributors 2015)*
Bridges	Road type, damage level, damage description	Shape-file	*(MLIT 2012; OpenStreetMap contributors 2015)*
Tsunami inundation extent	Inundation depth, inundation height, elevation	Shape-file	*(MLIT 2012)*
Japanese coastline	none	Shape-file	*(OpenStreetMap contributors 2015)*
Satellite imagery	none	Base map	*(ESRI contributors 2015; Google 2015)*

To develop fragility curves requires:

- Spatial hazard metric(s)
- Measured or descriptive spatial asset data
- Spatial non-damaged asset data
- Asset attribute information

Only assets that had been observed to experience some level of damage were recorded by the survey teams included in the database. This means that there were limited means to determine the ratio of damaged to undamaged assets. Observations of both damaged and undamaged assets are required to create a damage probability matrix which is used to develop a fragility function, otherwise a biased (over)estimate of damage will result. Asset inventory information is not publicly available for Japanese roads, therefore satellite imagery was used to complete the asset data sets within the inundation areas, as suggested by Eguchi et al. (2013).

Figure 3.2 displays the overall conceptual method used in this analysis. The data produced (damage probability matrix) was subsequently used by Horspool and Fraser (2015) for statistical analysis of fragility curves for generic roads and bridges. Building upon this, the present research also provides an analysis of road use type vulnerability to tsunami, for the development of a subsequent damage probability matrix of road use fragility. The statistical analysis of these are less sophisticated than that of Horspool and Fraser (2015).

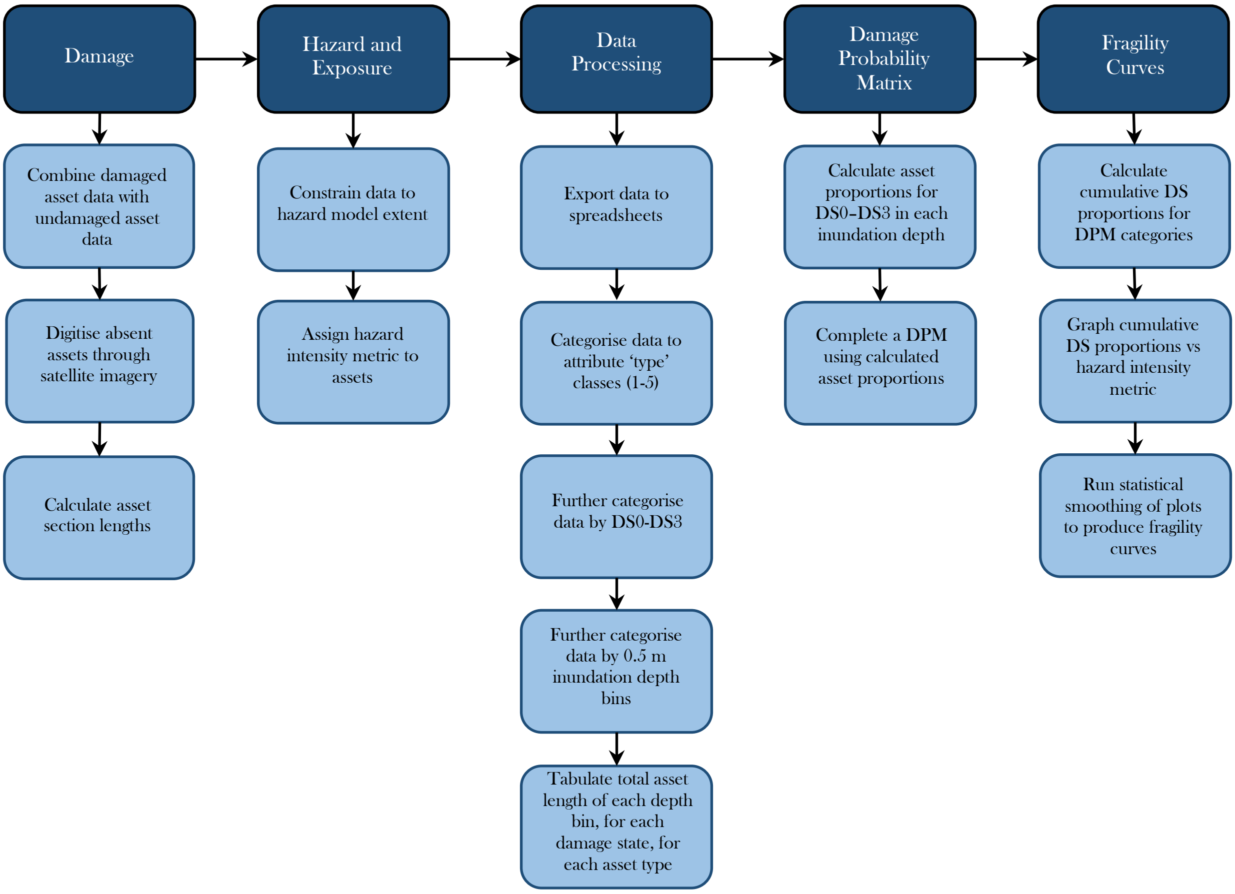

Figure 3.2: Conceptual method of vulnerability analysis of Japan roads. DS= damage state, DPM = damage probability matrix

3.2.1 Generic Roads Fragility Functions

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) data for roads had defined lengths with assigned damage states relating to the level of observed damage on each stretch of road. These are presented in Table 3.2, and examples shown in Figure 3.3. All roads missing from the data set were assumed to be undamaged, and were extracted from Open Street Map (OSM) or manually digitised from satellite imagery (OpenStreetMap contributors 2015; Google 2015; ESRI contributors 2015). This meant all roads within the inundation extent now had an assigned damage state (including no damage) and could be included in the analysis (Figure 3.4). The damage descriptions were converted to corresponding alphanumeric values of DS0, DS1, DS2 or DS3 for convenience.

Table 3.2: Damage state descriptions for roads. Note that DS0 was not included in data (MLIT 2012; Horspool & Fraser 2015)

Damage State	MLIT Damage State	MLIT Damage Description
0	None	*No Damage*
1	Minor	*Minor damage to road surface. All lanes passable*
2	Moderate	*Major damage to one lane. One lane impassable*
3	Severe	*Major damage to whole carriageway. All lanes impassable*

Figure 3.3: Examples of equivalent damage states observed in Coquimbo, Chile, following the 2015 'Illapel' earthquake tsunami

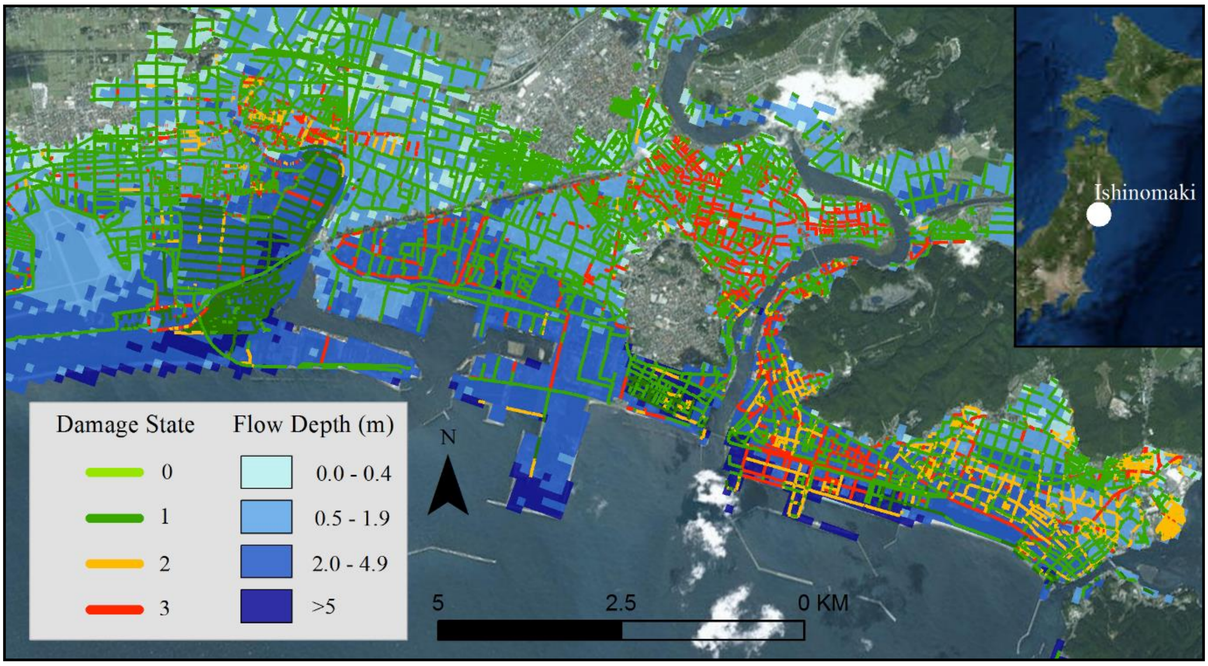

Figure 3.4: Damage states for roads in Ishinomaki, Japan, with maximum inundation depths (m) (MLIT 2012)

The next step involved assigning a hazard metric to the exposed assets. In this case tsunami inundation depth was used, given the availability of data and standardised use in previous tsunami fragility function developments, however other tsunami hazard metrics could be used, such as flow velocity or momentum flux (energy) (Shoji & Moriyama 2007; Horspool & Fraser 2015; Suppasri et al. 2013; Charvet et al. 2015). The road data were spatially assigned a corresponding flow depth based upon the provided MLIT tsunami inundation extent shapefile (Figure 3.5). Where a road segment crossed multiple flow depth grids, it was split into new segments. This meant the inundated roads could be grouped by both damage state and inundation depth.

The assigned attributes (inundation depth, damage state) and the road segment lengths were then exported to a spreadsheet where they were grouped by damage state (DS0 – DS3). Data were categorised into inundation depth bins of 0.5 m (i.e. 0 – 0.5 m, 0.6 – 1.0 m etc.). Once tabulated, these data were used to create a damage probability matrix by converting each damage state value to a proportion of total road length for each depth bin (e.g. Figure 3.6).

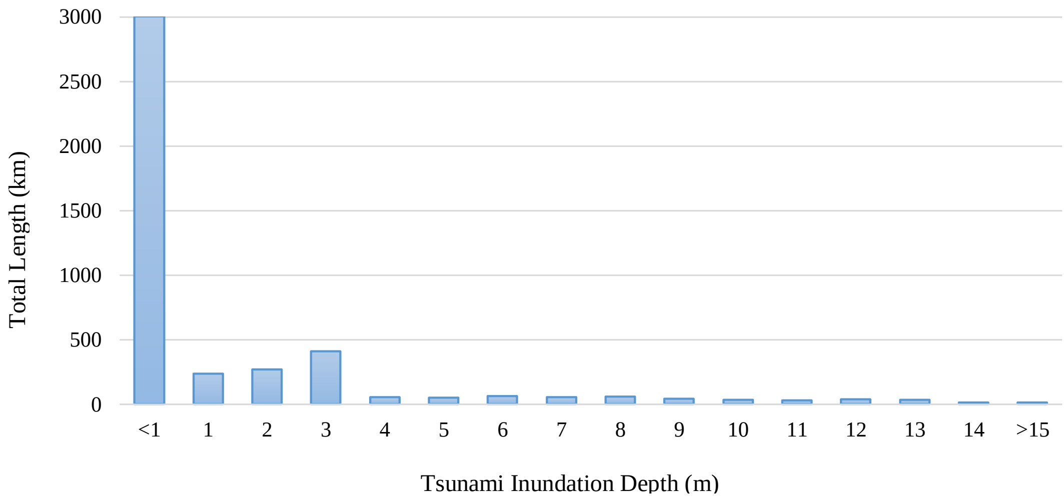

Figure 3.5: Road length totals at each 1m tsunami inundation depth bin, showing data volume for each catergory (MLIT 2013; OpenStreetMap contributors 2015)

The next step was to add the probability value of each damage state to the value of each greater damage state in the same depth bin (e.g. the probability of occurring in DS1 is added to the probability of occurring in DS2 and DS3). This creates a cumulative damage probability matrix and defines the probability of assets in each depth bin occurring in ≥DS1, ≥DS2 and ≥DS3 (Figure 3.7).

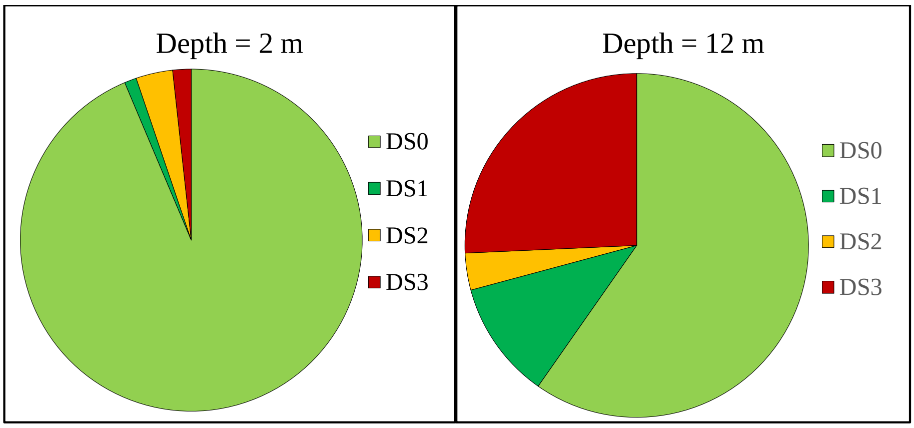

Figure 3.6: The proportion of damage states is defined for all roads at the 2 m and 12 m depth bins (MLIT 2012)

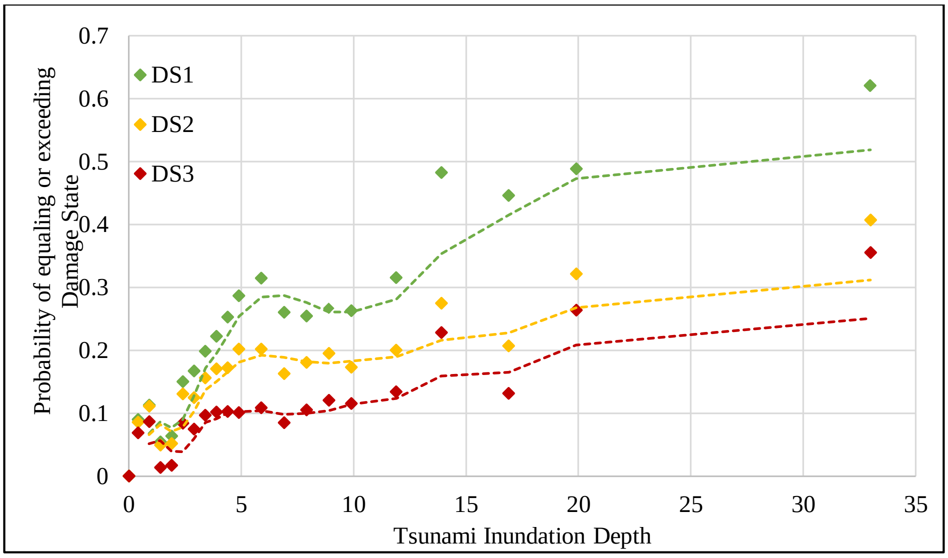

Figure 3.7: Cumulative probability plot for tsunami damage to roads with 3-point. moving average trend lines. Based on the analysis of Miyagi and Iwate Prefectures, Japan (MLIT 2012)

The analysis used for bridge damage probabilities was similar to that of roads, however inundation depth is normalised as height above the base of bridge decks. Open Street Map data already included bridges as a separate road attribute and so were easily integrated, and satellite imagery was used only to validate that all bridges were included in the data set. Any bridges that had been omitted were digitised manually. Bridge lengths were not necessary for the damage probability matrix, which uses bridge counts, therefore this attribute was not assigned to the data. Bridge construction materials were not available, neither was bridge deck height, both of which would be necessary for a higher resolution fragility function (Horspool & Fraser 2015; Shoji & Moriyama 2007).

As with roads, each bridge within the MLIT data set had an assigned damage state between DS1 & DS2 (Table 3.3). All non-surveyed bridges within the inundation extent were also assumed to be undamaged and consequently assigned DS0. All bridges within the inundation extent now had an assigned damage state and could be included in the analysis (Figure 3.8). To assign tsunami flow depths from the MLIT inundation extent shapefile, the centre point of each bridge was used. This was to avoid a bridge falling within multiple inundation depth bins.

Table 3.3: Damage state descriptions for bridges. Note that DS0 was not included in data (MLIT 2012; Horspool & Fraser 2015)

Damage State	MLIT Damage Description	MLIT Damage Description
0	None	*No damage*
1	Minor	*Minor damage, often from impacts to the superstructure*
2	Moderate	*Major damage to superstructure but still in place on piers. Superstructure may have been shifted*
3	Severe	*Complete washout of superstructure*

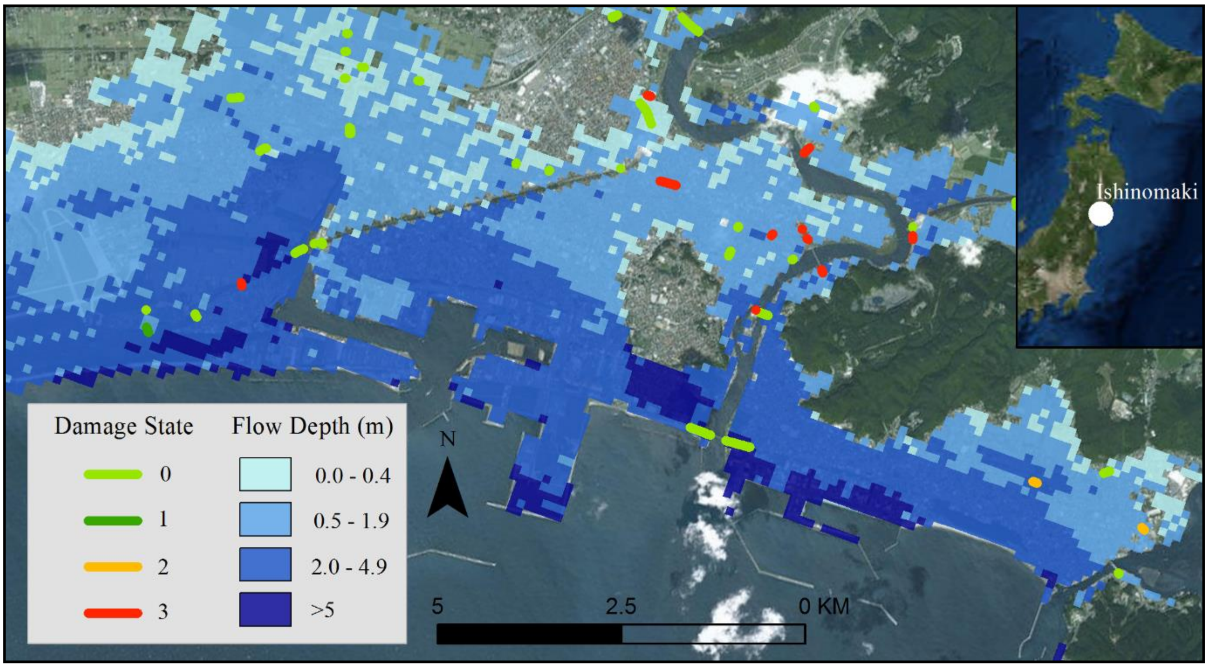

Figure 3.8: Assigned damage states for bridges in Ishinomaki, Japan, with maximum flow depths (m) (MLIT 2012)

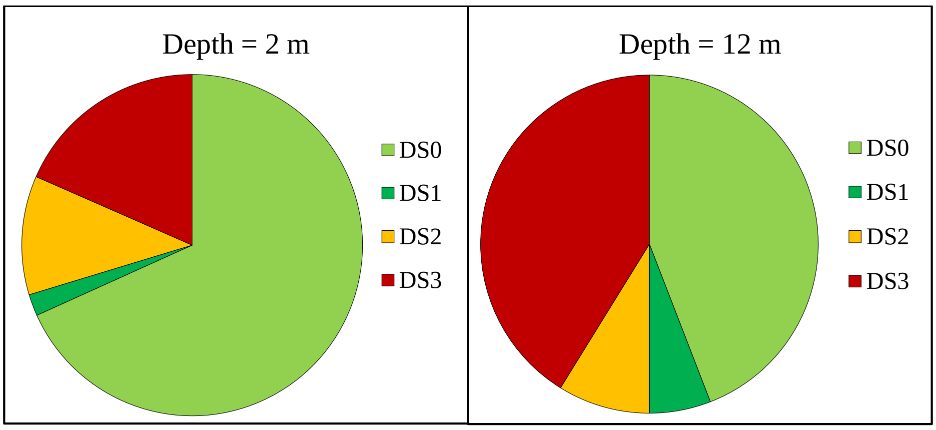

Figure 3.9: The proportion of damage states is defined for all bridges at the 2 m and 12 m depth bins (MLIT 2012)

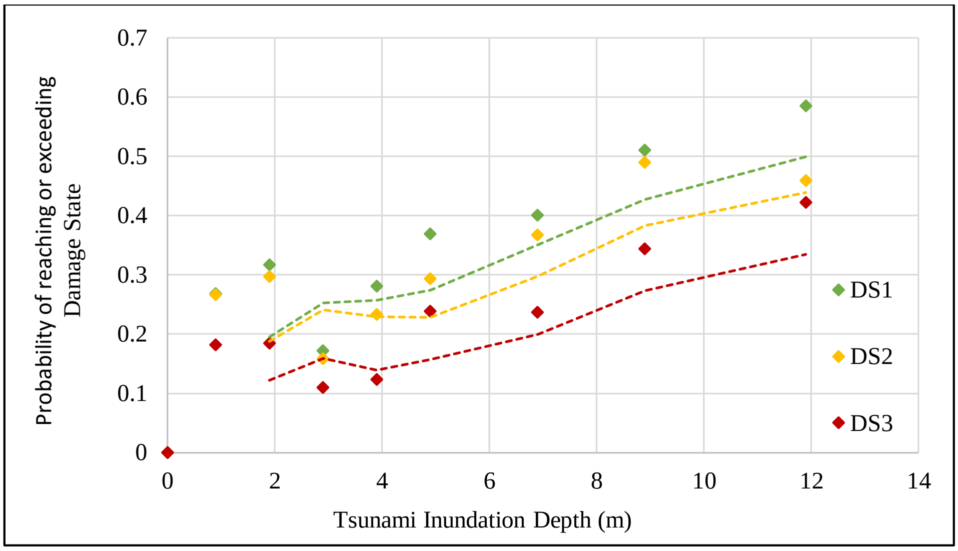

Figure 3.10: Cumulative probability plot for tsunami damage to bridges, with 3-point. moving average trend line. Based on the analysis of Miyagi and Iwate Prefectures, Japan (MLIT 2012)

Using data from the damage probability matrices developed in the present research, Horspool and Fraser (2015) developed fragility curves for each damage state of bridges and roads. Within their analyses, inundation depths for bridges were normalised to allow for an average of 5 m deck base heights, in the absence of attribute data. The cumulative damage probability data, from the present analysis, were first plotted as points, and a log-normal cumulative distribution function (CDF) curve applied to each damage state data set (Horspool & Fraser 2015). The log-normal CDF was chosen as it has been used to fit fragility curves for other tsunami damage analyses (Horspool & Fraser 2015; Shoji & Moriyama 2007; Suppasri et al. 2013). Each curve by Horspool and Fraser (2015) defines the probability of being in that damage state or greater as a function of tsunami inundation depth (m) for generic roads and generic bridges.

3.2.2 Road Use Fragility Functions

The goal of this work was to create a damage probability matrix for each construction type of a given asset. However, this relied on construction type, damage state, and inundation depth data being available for exposed assets.

In this case, the MLIT data did not contain construction type data for roads. To address this, the MLIT surveyed roads were categorised into broad pre-assigned 'Road Type' classes and then matched with 'Open Street Map' equivalents, as shown in Table 3.4. These were based upon spatial comparison and expert opinion (Davies, H, 2015, pers. comm., 6 August). This was not done for bridges as the 'road use' categories do not correspond so closely with construction types.

Table 3.4: MLIT road type categories and equivalent Open Street Map (OSM) classifications (MLIT 2012; OpenStreetMap contributors 2015)

MLIT Number	MLIT Classifications	OSM Classifications
(0/99)	Unclassified	Unclassified, No Data
(1)	State Road	Motorway, Trunk, Primary
(2)	The Main Local Road	Secondary
(3)	General Prefectural Road	Residential, Road,
(4)	Municipalities Road	Tertiary
(5)	Lowest Class Roads	Construction, Service, Unsurfaced

Many roads digitised from satellite imagery were assumed to be 'General Prefectural Roads' (3). However those that could not be classified were assigned to 'NoData' and have not contributed towards the damage probability matrices. Similarly, 'Unclassified' roads were also omitted. The data were grouped by type (1 – 5) (Figure 3.11) and the process of developing cumulative probability matrices was the same as described in section 3.2.1. This defined the cumulative probability of a road occurring within a damage state, as a function of inundation depth, for five different road types (e.g. Figure 3.12).

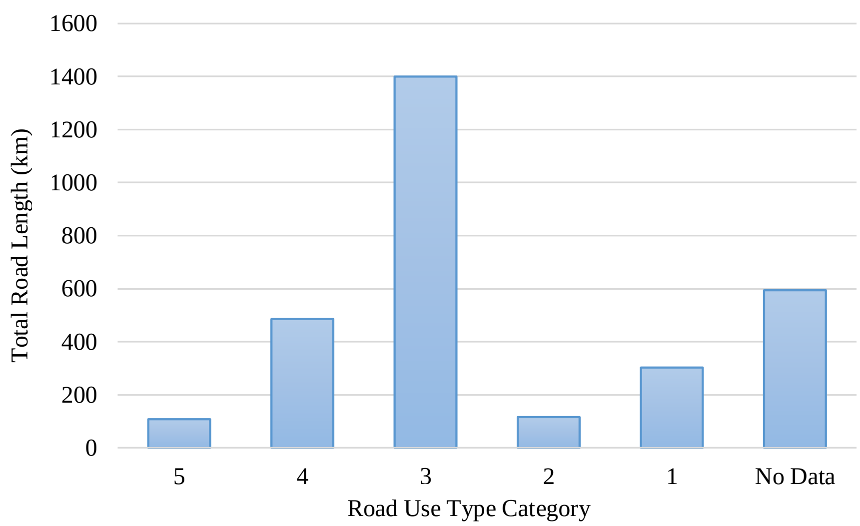

Figure 3.11: Total road lengths of each road type category, showing the volume of data in each category (MLIT 2013; OpenStreetMap contributors 2015)

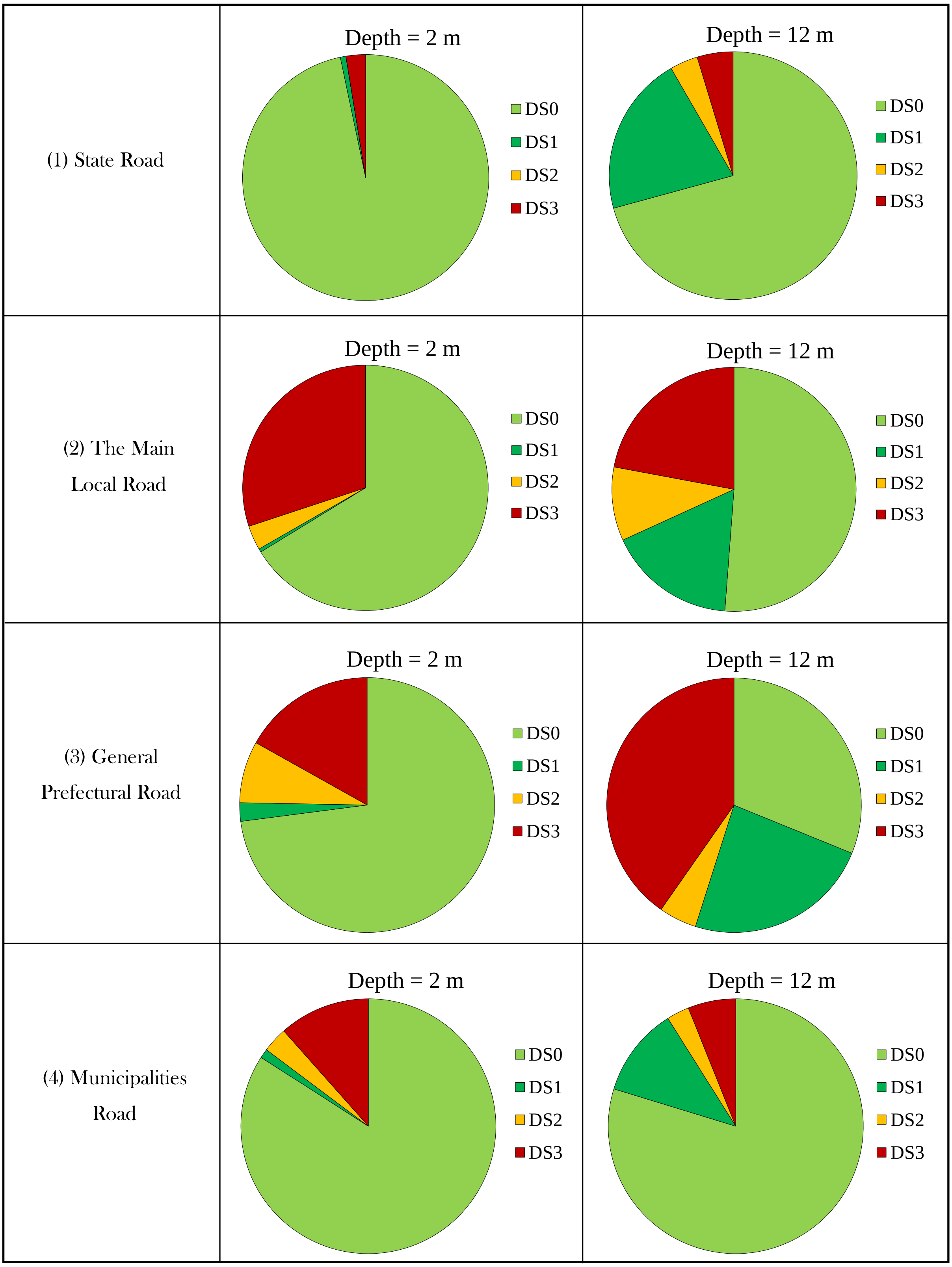

Figure 3.12: The proportion of damage states is defined for road types at the 2 m and 12 m depth bins. Note that (5) 'Lowest Class Roads' do not have sufficient data >2 m, therefore have been omitted here (MLIT 2012)

Using the 'Road Type' cumulative damage probability matrices, fragility curves were developed. The cumulative damage data bins were grouped in increasingly larger depth bins as inundation height increased. This was to take into consideration smaller sample sizes at greater inundation depths (see Figure 3.5).

Similar to the fragility curves developed by Horspool & Fraser (2015), the data were plotted as points, then a simple cumulative curve was applied to each damage state for each road use. Each curve defines a simplified probability of a road type being in a given damage state, or greater, as a function of tsunami inundation depth.

3.3 Results

In order to increase the resolution of tsunami impact modelling, fragility curves were developed for roads and bridges using post-disaster survey data. This is the first instance that quantitative fragility curves have been developed for tsunami impacts to roads, to the best of this author's knowledge, and the first for an infrastructure dataset of this size for tsunami damage.

Using the results displayed in Figure 3.13, it was found that roads in general performed well, even under the highest inundation depths. For example there is less than 0.2 probability of complete washout (DS3) at 15 m inundation depth. By comparison a reinforced concrete building has a 0.4 probability of complete washout at the same inundation depth (Suppasri et al. 2013).

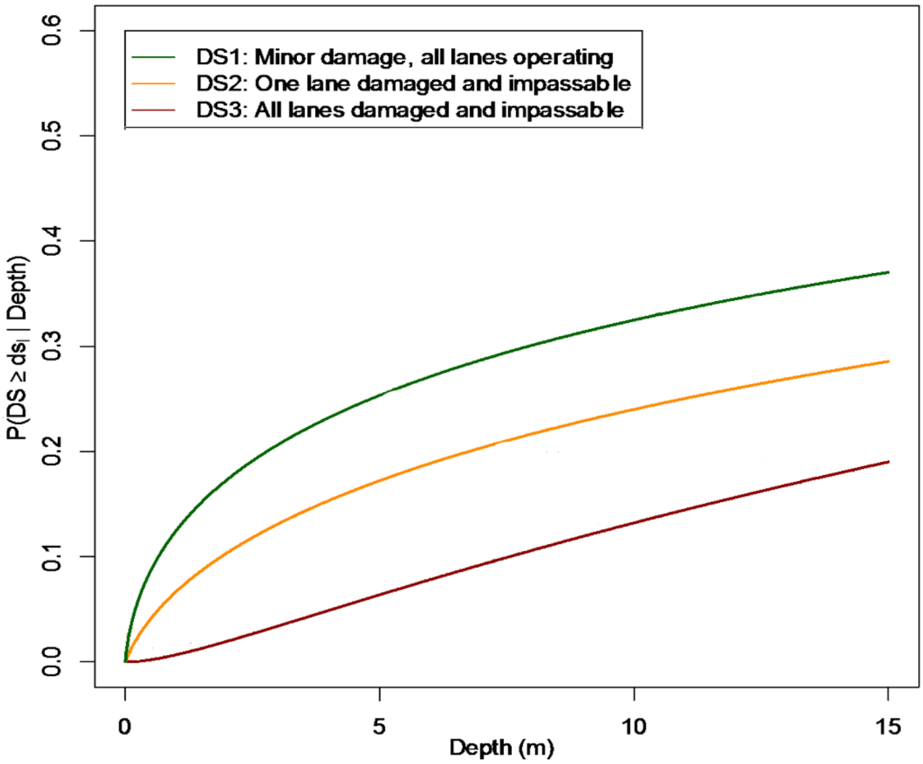

Figure 3.13: Fragility curves for generic road, based on the analysis of data from Miyagi and Iwate Prefecture, Japan (Horspool & Fraser 2015; MLIT 2012)

Figure 3.14 displays fragility curves for bridges, which appear to be more vulnerable to tsunami inundation than roads. For example generic bridges have a probability of 0.33 for being ≥DS3 at 10 m inundation, whereas roads have a probability of 0.08 at the same inundation depth. This is to be expected given a bridge's vertical profile and increased exposure when crossing channels. The lack of construction material data for bridges means that other fragility curves by Shoji & Moriyama (2007; described in Chapter 2) would perhaps provide a more realistic vulnerability metric. However, the MLIT data used here include almost five times as many bridges as the 'Indian Ocean Tsunami' data set used by Shoji & Moriyama (2007).

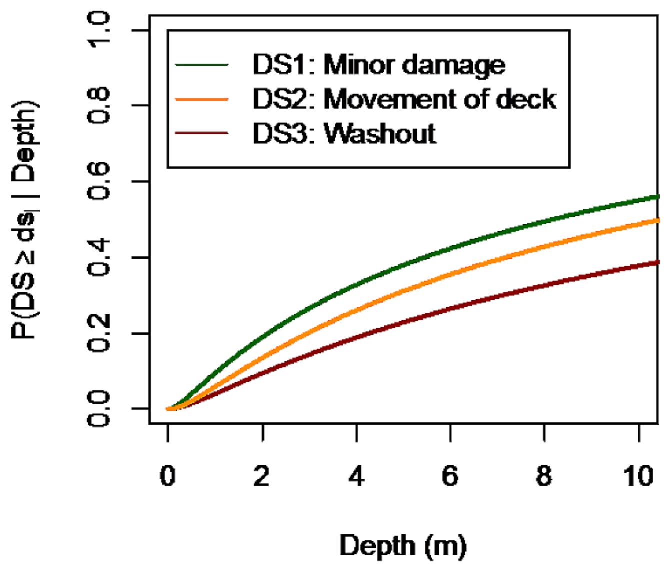

Figure 3.14: Fragility curves for generic bridges based on the analysis of data from Miyagi and Iwate Prefecture, Japan (Horspool & Fraser 2015; MLIT 2012)

In the road use fragility curves shown in Figure 3.15, road type 1 shows very low vulnerability to inundation depth which is unsurprising since this class would include Japan's most highly engineered road assets. This implies higher construction standards and stronger construction materials compared with other road types. Road types 2, 3 and 4 trend very similarly and likely share a similar spread of road construction materials. These also show significantly lower vulnerability to inundation depth than that of type 5 roads. Type 5 roads show very high vulnerability at even low inundation depths. This class most likely includes unsealed roads and would be extremely susceptible to erosion. Note that DS1 and DS2 for road type 5 did not have adequate data to present curves for. Subsequently just the curve for reaching or exceeding DS3 is shown.

The bridge fragility curves for DS2 and DS3 (Figure 3.14) are similar to those of the same damage states for the reinforced concrete curves in Shoji & Moriyama (2007), (Chapter 2). They are however at higher vulnerabilities than precast concrete and steel construction types. This is likely because the average Japanese bridge is comparable to the top end of construction standards for countries such as Sri Lanka and Indonesia, as used by Shoji & Moriyama (2007).

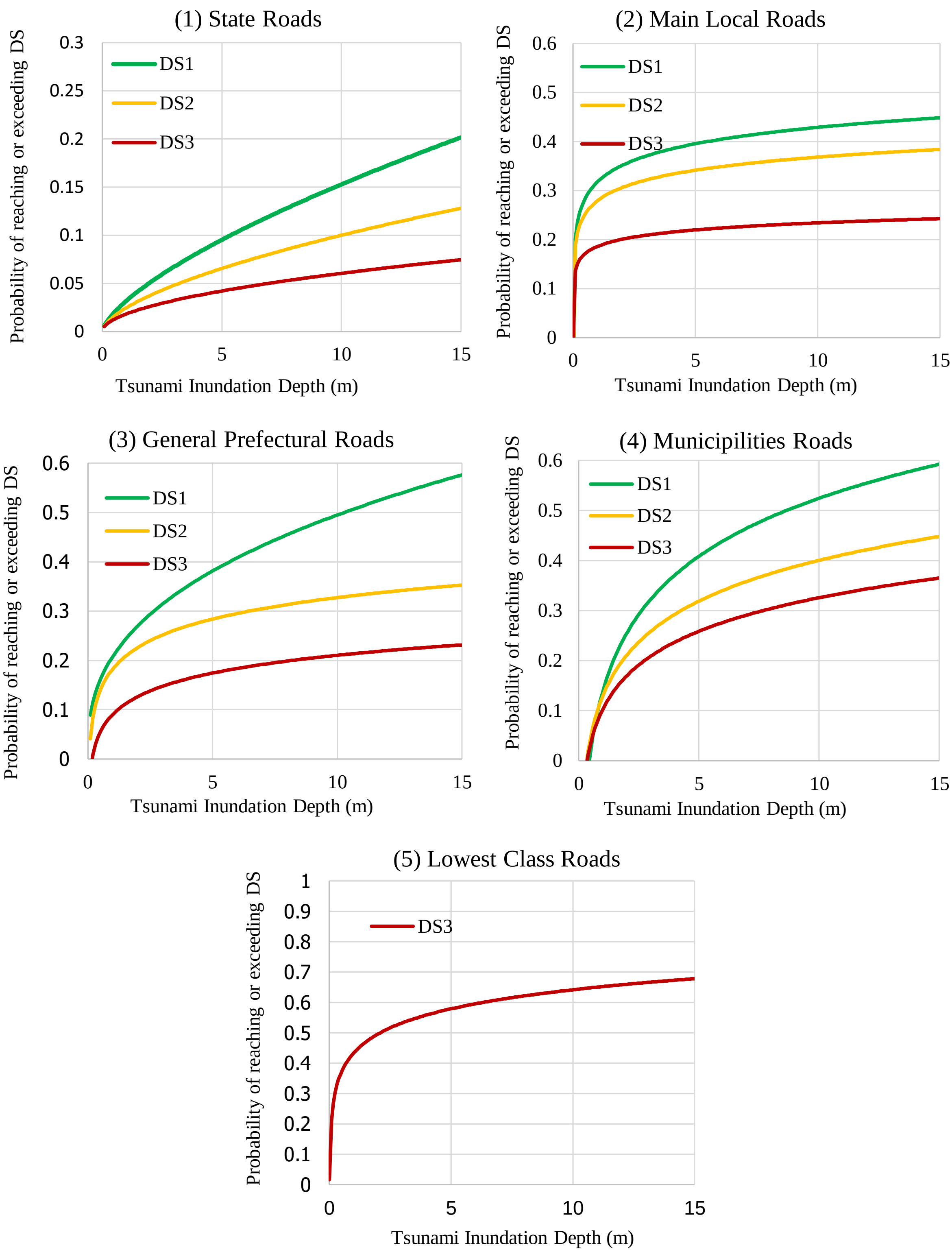

Figure 3.15: Fragility curves for road types 1 - 5 based on the analysis of data from Miyagi and Iwate Prefecture, Japan

Unlike Japanese roads, many described in the literature (Section 2.2) were not well engineered or were without well-compacted base materials. In the case of previous studies in places like Indonesia (e.g. Shoji & Moriyama 2007), some carriageways are laid directly onto loose sandy materials. This places great value on the Japanese survey data as construction standards there are typical also of New Zealand roads.

The generic road fragility curve (Figure 3.13) remains the most reliable to the application of an impact model, however the road type fragility curves (Figure 3.15) provide a valuable alternative in the absence of a construction type vulnerability metric. Fragility curves developed in this chapter, and subsequently by Horspool and Fraser (2015), provide the means to develop high resolution tsunami impact assessments for both roads and bridges. In the case of an impact model for Christchurch city, they will be used in place of the qualitative damage matrix to determine asset vulnerability, as described in Chapter 2.

3.3.1 Limitations of Results

As mentioned previously, this is the first time quantitative fragility curves for tsunami damage to roads have been developed. It is also the largest data set used in the development of fragility curves for bridges. However, as with all analyses, these results are not without their limitations.

Fragility functions for roads have been developed from the MLIT data by using road types (Figure 3.15). These delineate the vulnerabilities more realistically than using generic fragility curves. However these should be used with caution in tsunami impact assessments, as they are broadly categorised and each will have included construction materials that fall within multiple 'Road Use' categories. There will also inevitably be some inconsistencies in the conversion of MLIT road types to OSM road types. Any discrepancies could be due to translations, differing standards between countries and personal bias. There is also an element of judgement over how the damage states were assigned (Graf et al. 2014) and it is not entirely clear what types of damage are associated with each damage state (Eguchi et al. 2013). It is unknown if damage to the actual pavement is a prerequisite for a damage state assignment. For example it is not clear if DS1 includes debris coverage on an otherwise undamaged road.

Another concern with the 'road type' curves (Figure 3.15) is the lack of data for type 5 roads. This may pertain to an error in the data collection from unsealed roads, which can appear nonexistent in the field once silt and debris are deposited on top. This could also simply indicate a low threshold for damage, implying that once damage begins to occur on an unsealed road it rapidly becomes significant at any inundation depth. Nevertheless, a more gradual increase with inundation depth should be expected.

The damage probability matrices used for the fragility function development of both roads and bridges remain based upon the assumption that all roads within the inundation extent were surveyed for damage. This is the basis of assigning all non-surveyed roads to DS1. The analysis also assumed that all damage to an asset was exclusively from tsunami impacts. There was however likely damage associated with, or exacerbated by, the Mw 9.0 earthquake and subsequent aftershocks. This means that the weakening effect of the earthquake is not taken into account when applying the fragility functions to an impact assessment using a far-field tsunami scenario.

Although inundation depth is a widely used hazard metric for both tsunami and flood damage (e.g. Shoji & Moriyama 2007; Horspool & Fraser 2015; Suppasri et al. 2013), velocity of flow or momentum flux (energy) are also a determining factor in the distribution of damage during a tsunami (see Chapters 1 and 2). It is assumed that an 'inundation depth' metric also encompasses a metric of 'flow velocity' (i.e. greater maximum flow depths = greater maximum flow velocities). However flow velocity is more locally distributed than flow depth (which uses 100 x 100 m grids in this instance), due to the effects of hydrodynamic forces associated with changes in topography and obstructions.

To address some of these limitations, future post-event surveys should adhere to international post-event tsunami survey guidelines, such as those presented by Dominey-Howes et al. (2012). This would ensure future post-event field surveys include data relevant to all aspects of disaster management, including fragility functions. Also, if attribute data for pre-disaster Japanese assets become available (e.g. construction type and bridge deck heights), then fragility curves should be developed to include these, as a replacement for the road use curves above (Figure 3.15).
Despite their limitations, the fragility curves developed in this chapter are extremely useful for a tsunami impact assessment. The impact assessment of Christchurch city infrastructure will use both the generic road fragility curves from Figure 3.13 and the road type curves from Figure 3.15. This will provide a comparison of results, taking each method's limitations into account.

3.4 Summary

Fragility curves have been developed for roads and bridges using survey data following the 2011 'Tohoku' earthquake tsunami. The fragility functions developed are limited by available data but provide the first quantitative fragility function for tsunami road damage and the largest data set for bridge vulnerability. These will be used to increase the resolution of a tsunami impact assessment for Christchurch city infrastructure.

Chapter 4

Impact Assessment of Christchurch City Infrastructure

4.1 Introduction

The objective of this chapter is to present and critically discuss the results of a tsunami impact assessment undertaken for Christchurch city infrastructure for a far-field tsunami scenario. The results of an exposure assessment are first presented, and impacts on Christchurch city infrastructure are then shown for the given tsunami scenario. The scenario used (see Appendix 7.1) is from a Peru subduction zone source and was chosen as it represents an extreme event for Christchurch city. This includes asset exposure summaries and damage probability maps for each infrastructure network. A simple 'level of service' assessment summarises the results. The results are critically discussed and implications for the greater Christchurch city area are taken into account. To conclude this chapter, possible response and mitigation options are identified.

This chapter draws on outputs from Chapters 2 and 3 within the impact assessment model. Specifically, the qualitative tsunami damage matrix for infrastructure is used from Chapter 2. While quantitative fragility curves for roads and bridges are used from Chapter 3. See Table 2.6 for the most applicable vulnerability metric for each available Christchurch city asset. These are used for the specified assets in this tsunami impact assessment as they represent the highest resolution data available for their respective elements as discussed in Chapter 2. Note however that electricity network assets are absent from the assessment. This is due to accessibility restrictions on asset data within the time restraints of this thesis.

4.2 Asset Exposure

The objective of this section is to present results from a tsunami exposure analysis of Christchurch city infrastructure. It is based off the given tsunami scenario (Appendix 7.1) and is the first step data processing step in the impact assessment process (Figure 1.2). All available assets have been assigned a measure of hazard intensity for the purpose of later assigning an associated measure of vulnerability.

The tsunami exposure (inundation depth) of each available Christchurch city infrastructure asset is presented in Table 4.1 and a map of Christchurch infrastructure assets is presented in Figure 4.1 for context. These are measured in kilometre lengths for network assets (such as roads) and counts for network nodes (such as cellular towers). Kilometre is used as a metric of length given the large volume of exposed network asset spans (e.g. Figure 4.1). Potable water has the highest exposure to tsunami inundation in this scenario, with over 167 km inundated. However, in terms of above-ground infrastructure, roads have the highest exposure with over 130 km inundated. Potable water and roads are also the first and second most exposed assets to inundation depths over 2 m.

Table 4.1: Summary of Christchurch infrastructure exposure to tsunami inundation. Pump stations refer to the wastewater network. Bridge inundation refers to height above deck base

	Impact Lengths (km)					***Impact Counts***			
Inundation Depth (m)	*Stormwater*	*Roads*	*Wastewater*	*Water Supply*	*Rail*	*Cell Sites*	*Bridges*	*Pump Stations*	*Fuel Storage Tanks*
<1	21.8	58.8	36.1	70.5	.5	6	7	4	15
1 - 1.9	12.7	36.7	23.8	43.4	1.1	7	1	3	16
2 - 2.9	9.1	20	14.6	24.7	.7	5	2	2	0
3 - 3.9	5.5	13.8	11.7	17.8	0	2	0	1	0
4 - 5	3.5	4.2	5.6	8.4	0	1	0	2	0
>5	.1	.5	.23	2.4	0	0	0	0	0
Total Impacted	52.7	134	92	167.2	2.3	21	10	12	31

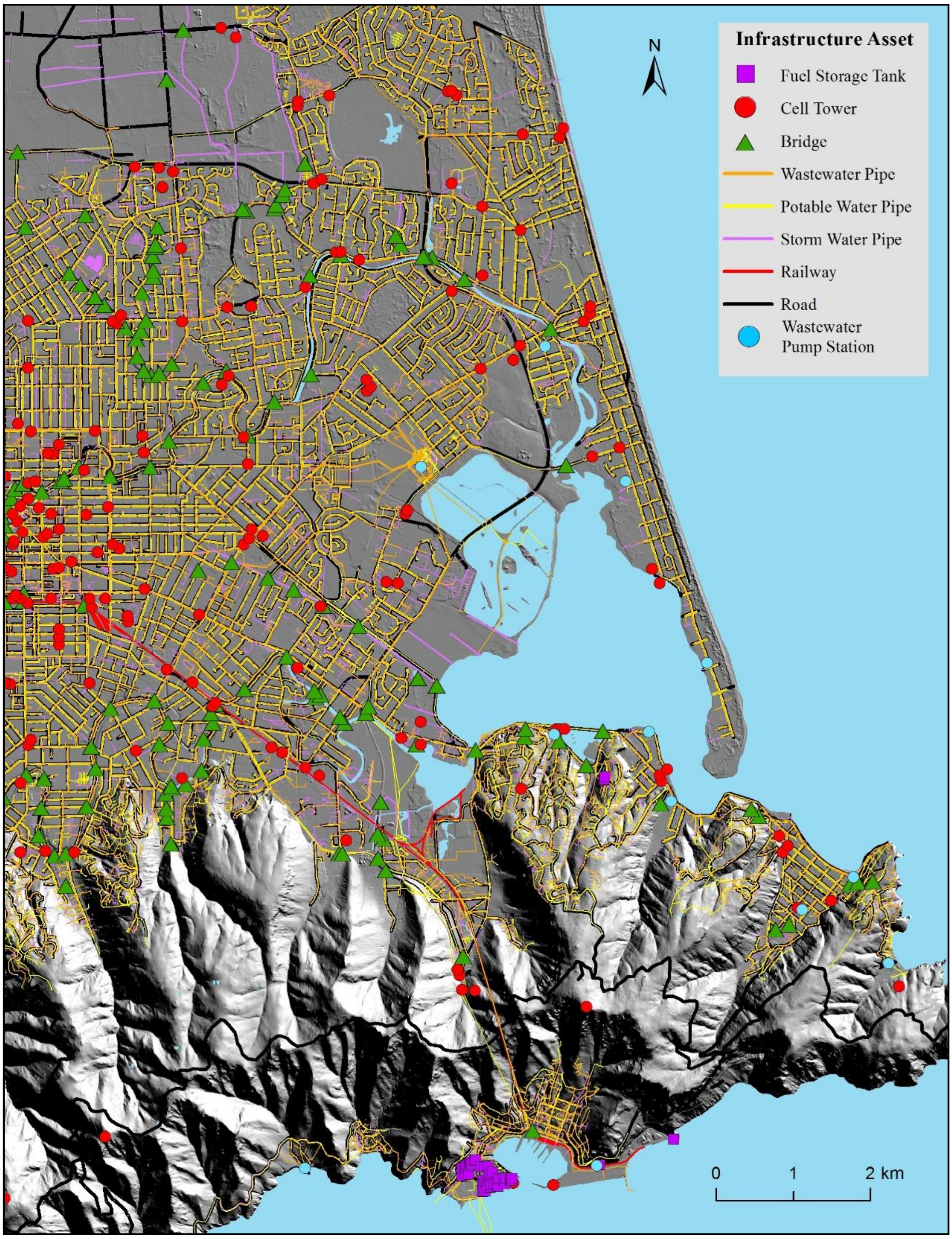

Figure 4.1: Map of Christchurch city infrastructure assets. For asset data sources see Table 2.5

4.3 Infrastructure Impacts

Tsunami impact assessment results are presented in the section below, indicating probabilities of damage for infrastructure networks. First, results for assets which had quantitative vulnerability metrics available are presented, followed by assets for sectors using qualitative vulnerability metrics. These apply to the methods defined in Chapter 2. Christchurch city suburbs referred to in this section can be found in Appendix 7.6.

4.3.1 Transport

4.3.1.1 Roads

The road transport impact models use quantitative fragility curves, developed in Chapter 3, as hazard metrics. Both generic fragility curves and ones which take road use into account have been modelled for comparison, as they each have their own benefits and limitations as discussed in Chapter 3. Figure 4.2 displays results of a model using generic fragility curves for roads and bridges (Horspool & Fraser 2015), while Figure 4.3 uses 'Road Type' fragility curves for roads. Bridges are modelled exclusively with generic curves and do not differ between road models. Results are presented as the probability of reaching or exceeding DS2, which is equivalent to significant damage occurring.

The generic road model (Figure 4.2) suggests that most roads will range from <0.05 – 0.2 in probability for significant damage occurring, the highest of which are in Sumner and Moncks Bay, as well as in New Brighton and South Shore. Comparatively, when defining vulnerabilities for road use types, the model presented in Figure 4.3 suggests probabilities mostly <0.1 – 0.3 of significant damage occurring. The highest probabilities occur in Sumner (0.3 – 0.35), with similar values also represented in New Brighton and South Shore.

Bridges appear to have even lower probabilities of damage using a generic vulnerability metric (<0.2), and most have a 0.0 probability of significant damage occurring (Figure 4.2). This is surprising given that they were deemed more vulnerable in a review of literature (e.g. Akiyama et al. 2013) and the development of fragility curves presented in Chapters 2 and 3. This may come down to the lack of bridge height data used as an input for the generic fragility curves. As discussed in Chapter 3, bridge deck heights were all assumed to be 5 m above ground level. This was to normalise inundation depth values as a depth above the base of a bridge deck. The lack of construction type data was also noted as a limitation to these curves in Chapter 3. Subsequently higher probabilities of significant damage could presumably be expected for areas of high inundation depths (e.g. in Sumner) for bridges of lower construction standards (e.g. wooden bridge).

These results present relatively low probabilities of significant damage for road transport assets. Based on these, on average Christchurch city could expect around 15% of roads exposed to tsunami inundation to be significantly damaged in this given scenario (likely concentrated mostly in the suburb of Sumner).

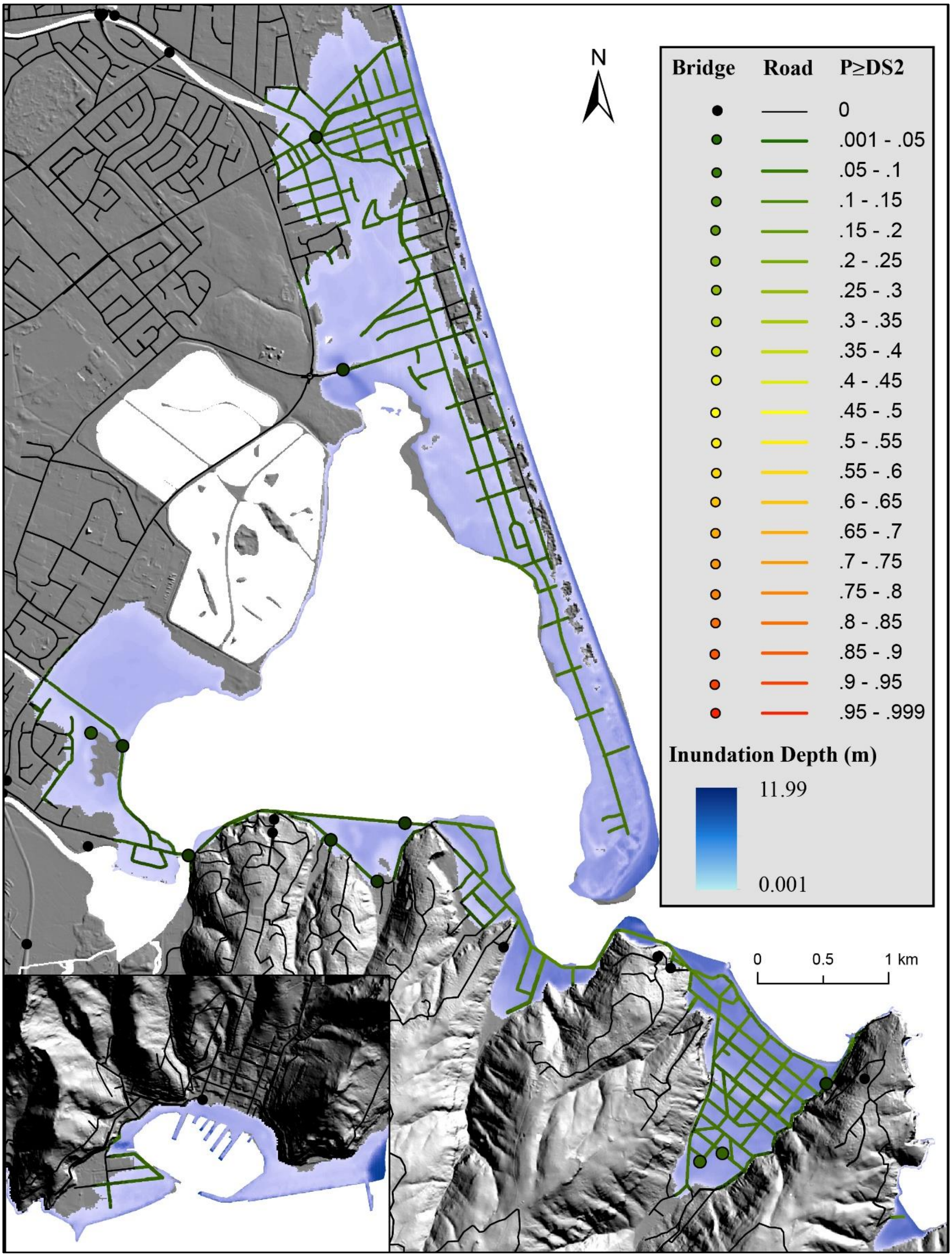

Figure 4.2: Modelled probability of Christchurch city roads and bridges reaching or exceeding DS2 in a tsunami scenario, using generic fragility curves

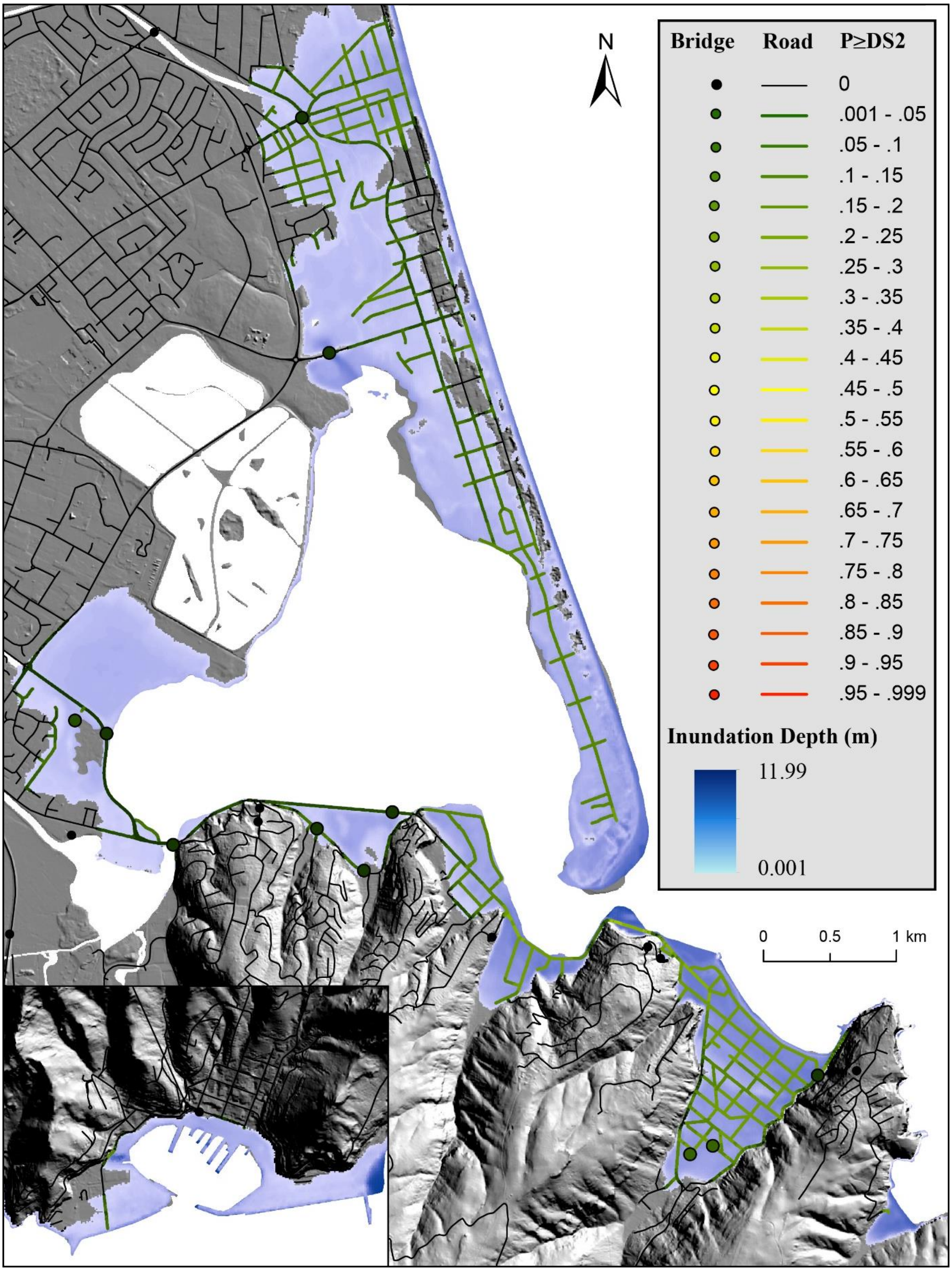

Figure 4.3: Modelled probability of Christchurch city roads and bridges reaching or exceeding DS2 in a tsunami scenario, using 'road use' fragility curves

To more clearly see the differences between these two models, Figure 4.4 provides a closer look at the suburb of Sumner. Here the differences between the two vulnerability inputs are slightly more evident. The 'road use' model (right) suggests more contrasting damage probability, with slightly higher values evident, in comparison to generic road vulnerability modelling (left). The 'road use' vulnerability model also has damage probabilities slightly less constrained by inundation depth than that of the generic fragility model. This indicates variations in road construction standards associated with the road use categories constrained in Chapter 3. Note that bridges use the same vulnerability input and show no variation between the two models.

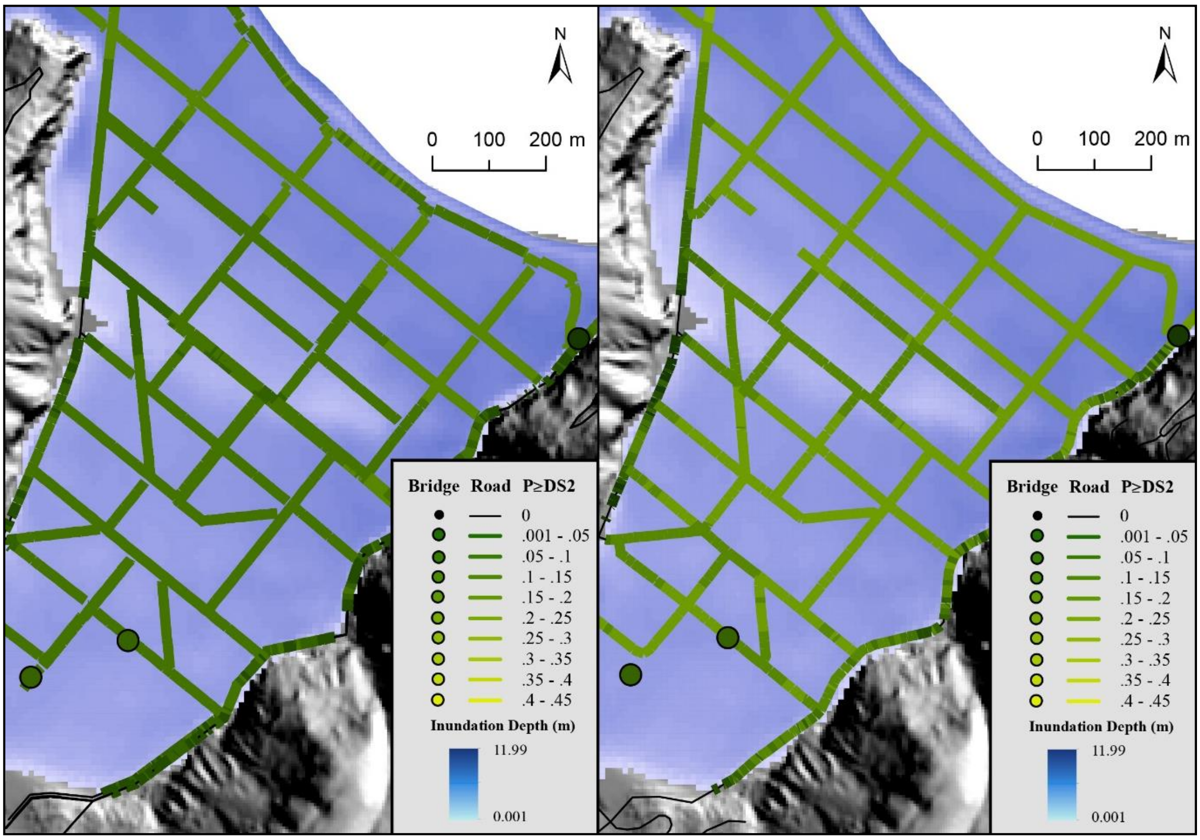

Figure 4.4: Modelled probability of roads and bridges reaching or exceeding DS2 in a given tsunami scenario, for the suburb of Sumner, using generic (left) and 'road use' (right) road vulnerability metrics. Bridges use a generic vulnerability metric in both models

4.3.1.2 Port

The modelled assets for tsunami impacts to ports are limited to wharves, as outlined in Chapter 2. However, included in this subsection are impact models for both rail and petroleum. Rail is included, as the relevant assets are only exposed to tsunami inundation within the confines of the port for the present scenario. Petroleum fuel storage tanks have been included in the results for ports due to the spatial exclusivity of relevant assets in Lyttelton Port. It should be noted however that these fall into the energy infrastructural sector. Wharves and rail both use a damage matrix method as outlined in Chapter 2. Fuel storage tanks use a generic quantitative damage curve (Hatayama 2014), allowing a numeric probability of damage to be determined. As discussed in Chapter 2, this provides a less subjective and higher resolution vulnerability metric than that of a qualitative one. It may be useful in future research to treat the port as a single entity, thereby using the same vulnerability metric (i.e. tsunami damage matrix) for all assets. The current approach does not allow for easy comparison as the data have not had the same level of treatment. One could argue that it is preferable to model all assets with the same level of accuracy, however the approach used here takes the highest resolution vulnerability metric available (i.e. fragility curve), as outlined in Chapter 2.

The model presented suggests that wharves have high probability of damage (Figure 4.5). This is unsurprising given they are one of the most exposed assets to tsunami inundation in terms of depth, velocity and duration. Results for the rail model indicate that exposed assets are largely at medium to high probabilities of damage occurring. It is also likely that ballasts would be scoured and tracks extensively covered with debris given the proximity to port facilities and their location at the base of a confining slope (Figure 4.5). Debris could include shipping containers, vehicles and vessels. The model for fuel storage tanks (Figure 4.5) suggests all exposed tanks are below 0.15 probability of damage occurring. This is dependent however on the volume of liquids inside (Scawthorn et al. 2006; Cruz et al. 2009; PIANC Working Group 53 2009) and the construction type of tanks, both of which are excluded from this assessment.

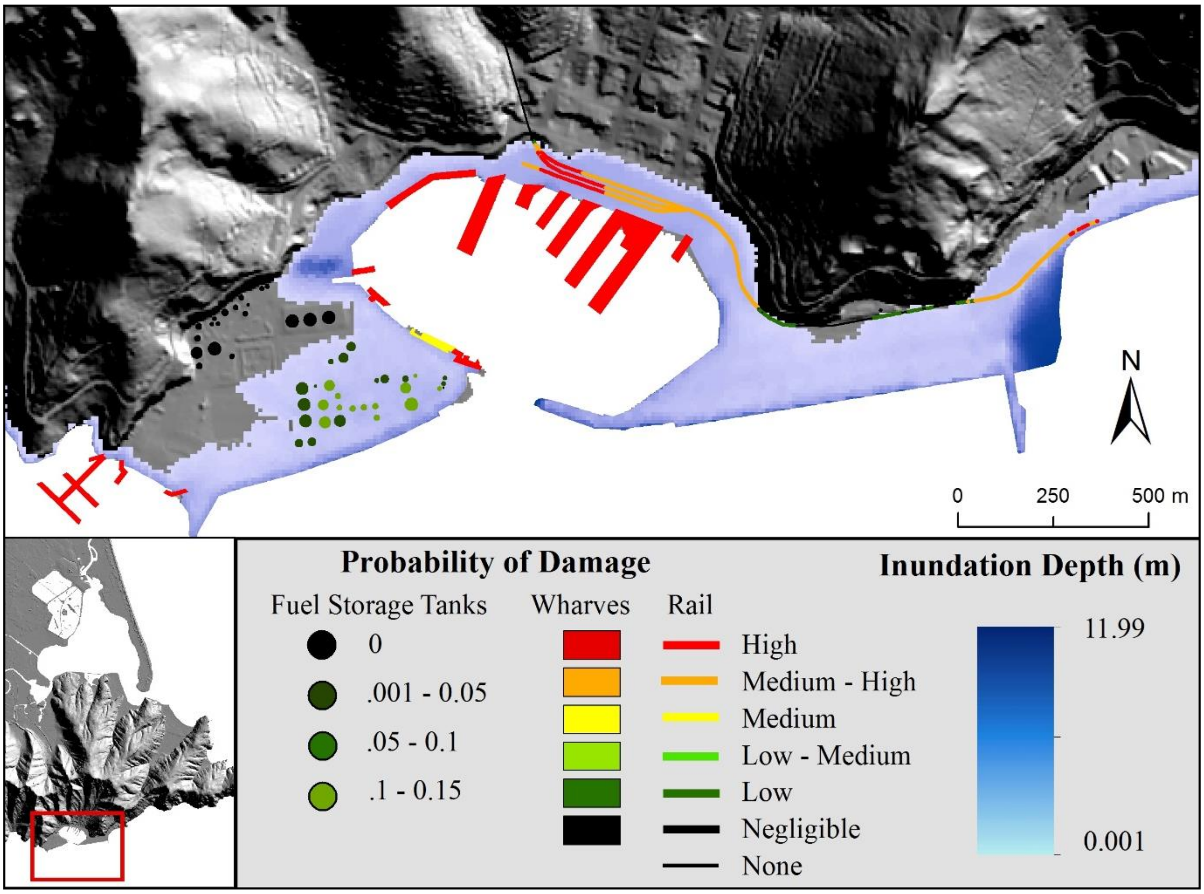

Figure 4.5: Modelled probability of tsunami damage for Lyttelton Port, including wharves, rail and fuel storage tanks

4.3.2 Water

4.3.2.1 Wastewater

The model for wastewater assets uses the damage probability index method (Chapter 2). It indicates low to medium probability of damage occurring within the inundation zone for wastewater pipes (Figure 4.6). The largest concentrations of pipes with medium probability of damage are in Sumner, Moncks Bay and New Brighton (see Appendix 7.4). New Brighton, Redcliffs, Taylors Mistake and Lyttelton all have small concentrations of pipes at a medium probability of damage, while Sumner pipes are largely at a medium probability of damage. The most noteworthy damages are the medium probability associated with the Ferrymead Bridge and the link between Moncks Bay and Sumner. Significant damage at either location could result in loss of service, or a bypass of treatment facilities. Also included in this model are wastewater pump stations. These are necessary to pump waste up-slope to the treatment plant from eastern suburbs. The model suggests these are largely at high probability of damage. It should be noted that for the given tsunami scenario the Christchurch city wastewater treatment plant is not exposed to any level of tsunami inundation other than low inundation depths around the flanks of the eastern most treatment pond's stop-bank (Figure 4.6). Since the hazard model uses fixed topography, scour is not considered for this feature, and stop-bank impacts from tsunami are not assessed in the present research. Future research is recommended on the vulnerability of the stop-bank and whether a breach would impact the functionality of the wastewater treatment plant facilities.

4.3.2.2 Potable Water

Using the damage matrix method, the model for tsunami impacts on potable water implies that pipes have a low to medium probability of damage occurring (Figure 4.7). The spatial distribution of damage probability is the same as with wastewater pipes (Figure 4.6). If construction type or material variations were included in the analysis, the results would likely be much less constrained by inundation depth between these two similar networks. New Brighton, Redcliffs, Lyttelton and Sumner all have pipes at a medium probability of damage, while Sumner pipes are largely at a medium probability of damage. A notable observation is the medium probability of damage occurring to pipes south of Lyttelton Port, which supply water to the other side of the harbour and are exposed to the strong currents produced by a tsunami traveling in and out of the harbour.

4.3.2.3 Stormwater

Using the damage matrix method, the modelled results for stormwater pipes indicate a range from low-medium to medium probability of damage for most assets (Figure 4.8). This is slightly higher than wastewater and potable water. As mentioned in Chapters 1 and 2, although pipes are generally of similar construction to wastewater, they are often at significantly shallower depth and thus much more vulnerable to damage from debris impacts and soil erosion. As with the other two water networks (Figures 4.6 and 4.7), Sumner is almost completely at a medium probability of damage occurring for stormwater pipes.

The only variation in vulnerability metrics for stormwater is the distinction of open drain channels from buried stormwater pipes. Open drain channels (located largely just south-west of the wastewater treatment ponds) are all at a high probability of damage, as inferred by this model (Figure 4.8). This may be due to a higher degree of exposure, being an uncovered waterway. They are also a likely flow path for tsunami waters, which could increase the chances for some degree of scour or debris deposition. In saying this, damage to these channels is unlikely to affect their functionality for drainage purposes, unless they are entirely infilled with tsunami deposits.

It is also worth noting that street gutters are an integral part of the stormwater network, but are not constrained in the present research. In addition to buried stormwater pipes being compromised, the presence of debris and sediment on roads (e.g. Appendix 7.4) could exacerbate impacts on the functionality of stormwater infrastructure. This could in part be inferred by the impacts to roads.

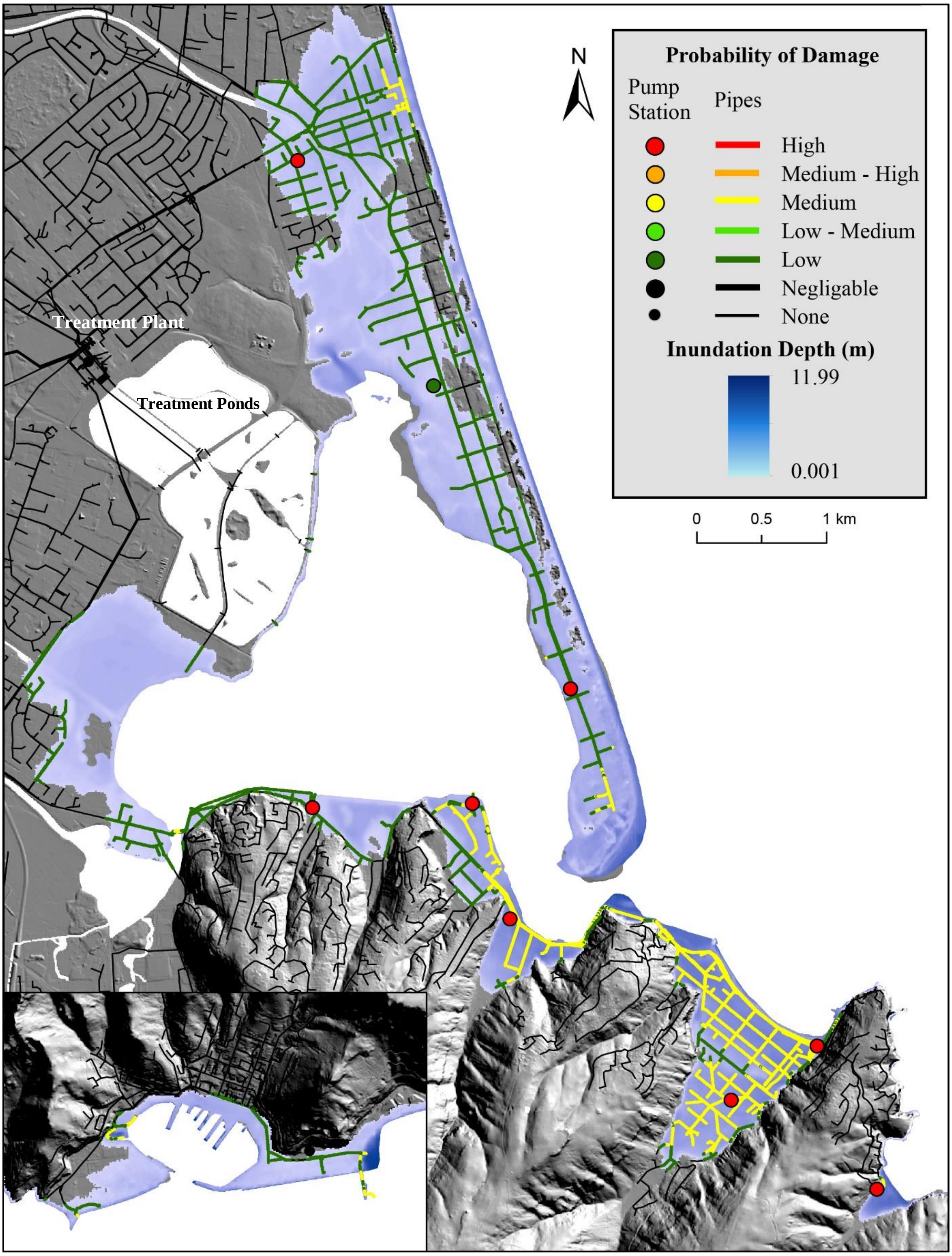

Figure 4.6: Modelled probability of tsunami damage occurring to wastewater network in Christchurch city.

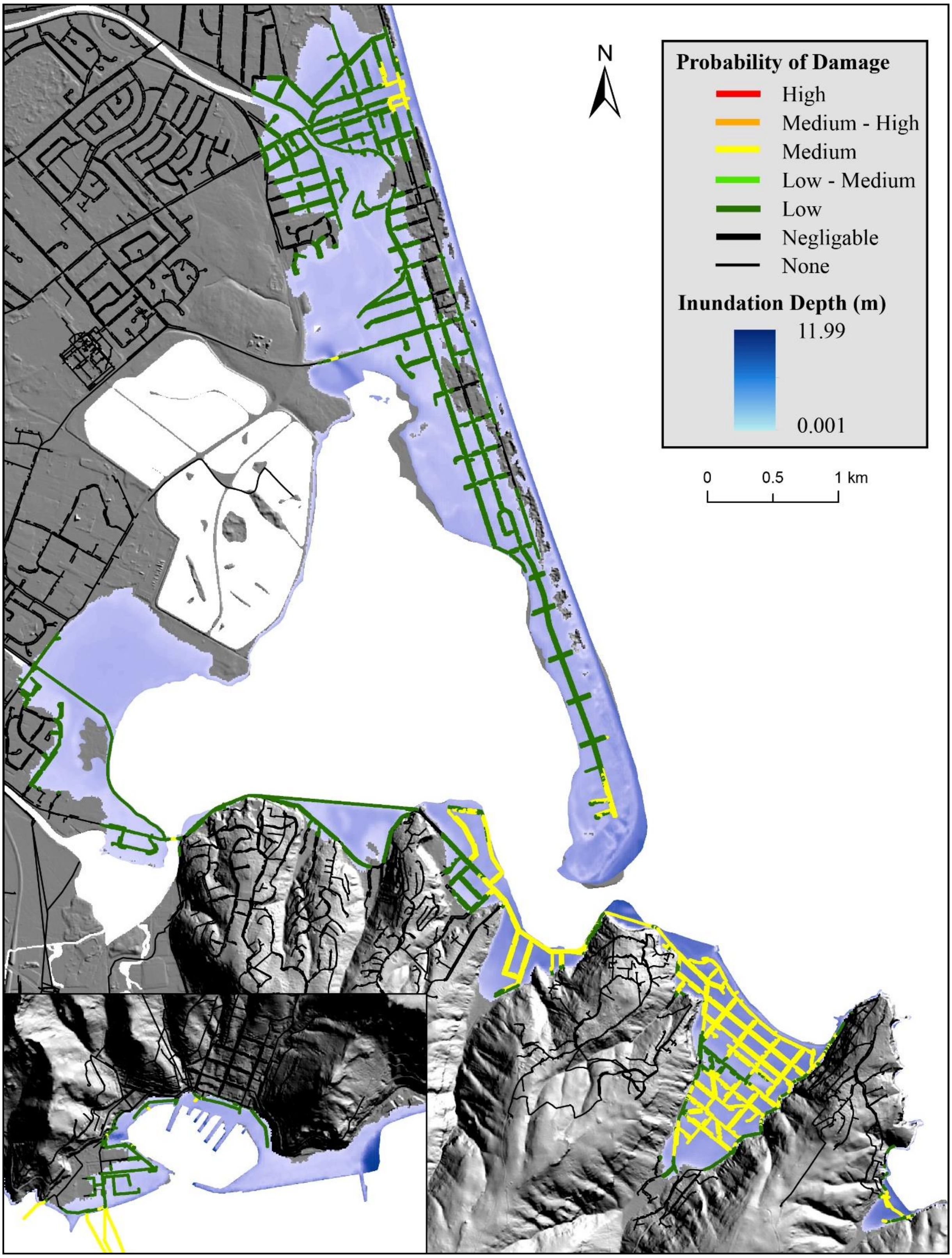

Figure 4.7: Modelled probability of tsunami damage occurring to potable water network in Christchurch city

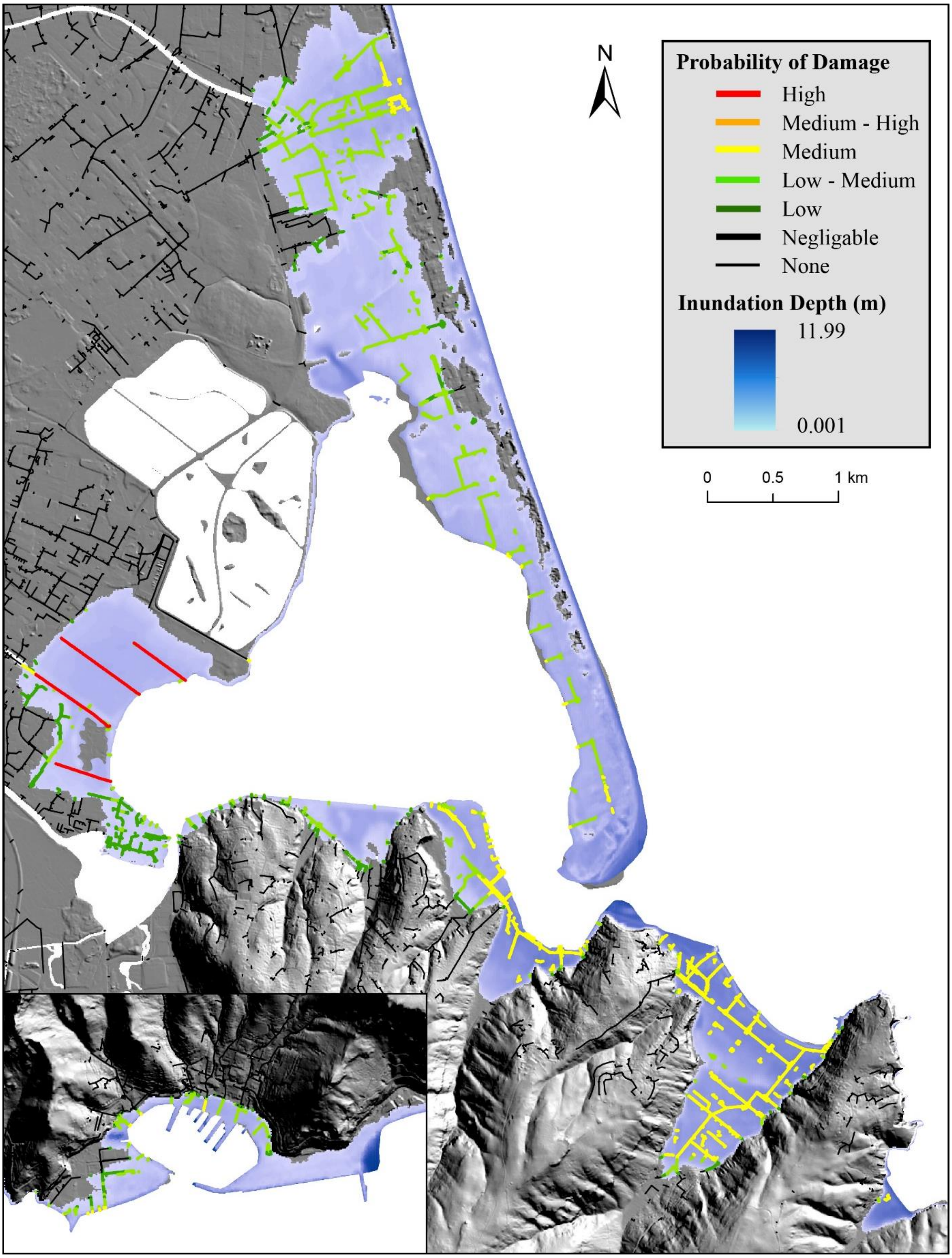

Figure 4.8: Modelled probability of tsunami damage occurring to stormwater network in Christchurch city

4.3.3 Telecommunications

The tsunami impacts model for cellular towers uses the tsunami damage matrix from Chapter 2 as a vulnerability metric. The model suggests a large proportion of towers are at high probability of damage occurring in the given scenario (Figure 4.9). Only two exposed towers, in Ferrymead and Mt Pleasant, are exempt from a high probability of damage.

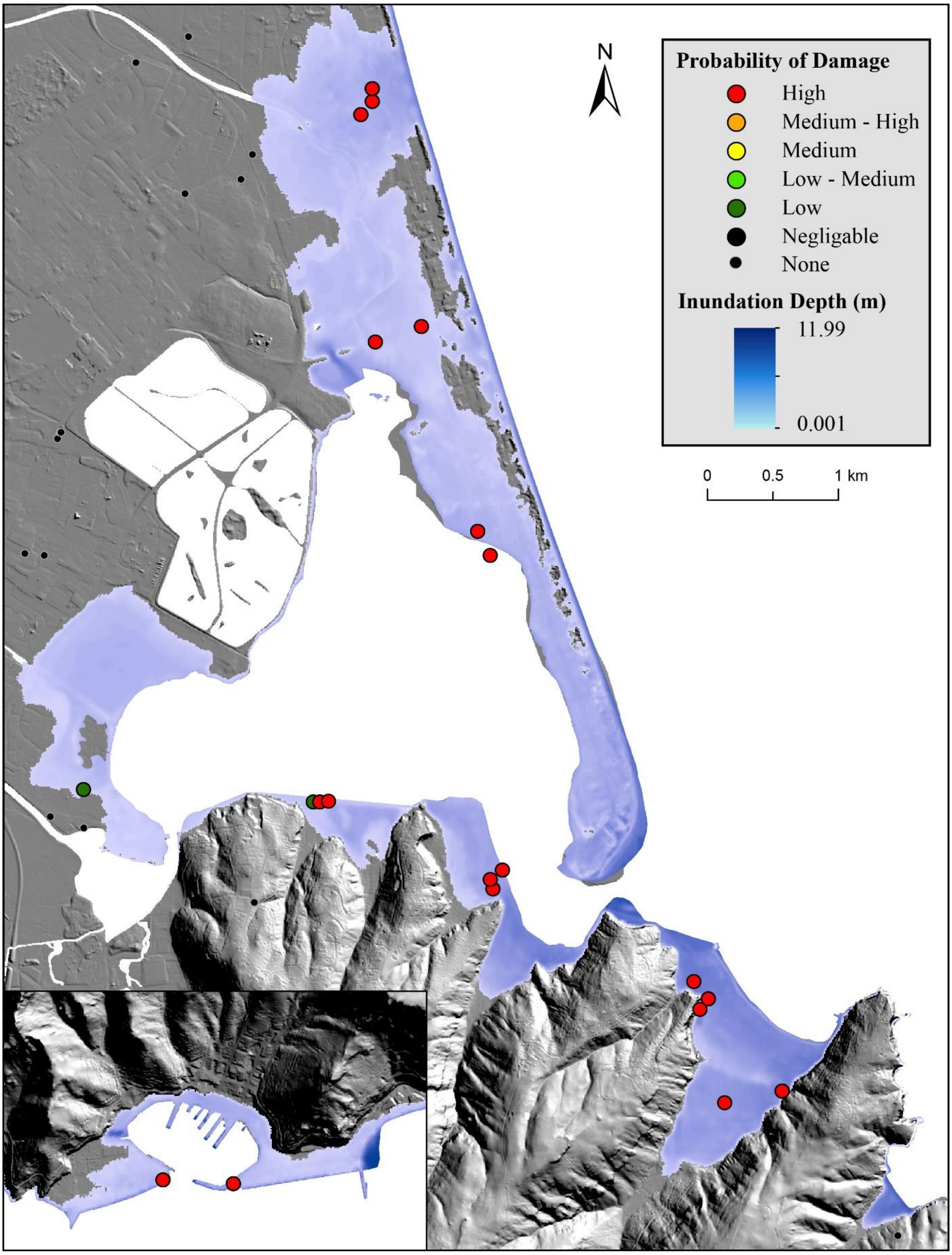

Figure 4.9: Modelled probability of tsunami damage occurring to cellular towers in Christchurch city

4.4 Levels of Service

Results from a level of service analysis are presented in Table 4.2. By grouping each infrastructure sector by suburb, a measure of serviceability has been assigned, determined by whether the service would likely be available or would likely not be available for each network (i.e. within hours following the final damaging wave). These were determined using an entirely subjective, logic-based, decision-making approach (presented in Appendix 7.5) by the author based upon each network's probability of damage in each suburb (outlined in Chapter 2). This took into account higher probabilities at network bottlenecks and other key network nodes (e.g. pump stations for wastewater), as well as the presence of network redundancies.

Table 4.2: Level of infrastructure network service for exposed Christchurch city suburbs following the given tsunami scenario.

Suburb	**Network**						
	Wireless Telecoms	*Potable Water*	*Storm Water*	*Waste Water*	*Road Access*	*Rail*	*Port*
Waimairi Beach	Yes	Yes	Yes	Yes	Yes	N/A	N/A
North Beach	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Rawhiti	Yes	Yes	No	Yes	No	N/A	N/A
New Brighton	Yes	No	No	No	No	N/A	N/A
Aranui	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Bexley	Yes	No	No	No	Yes	N/A	N/A
South Brighton	Yes	No	No	No	No	N/A	N/A
South Shore	Yes	No	No	No	No	N/A	N/A
Bromley	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Ferrymead	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Heathcote Valley	Yes	Yes	Yes	Yes	Yes	Yes	N/A
Mt Pleasant	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Moncks Bay	Yes	No	No	No	No	N/A	N/A
Sumner	No	No	No	No	No	N/A	N/A
Lyttelton	Yes	Yes	Yes	Yes	Yes	No	No

The exposed suburbs are broadly listed from North to South (See Appendix 7.6) and clear patterns are evident across the various networks. The areas modelled with higher damage occurrence probabilities are expressed more commonly here as having a subsequent loss of service (for example, stormwater in Sumner and New Brighton). This does not take into account the cascading impacts of interdependent network losses.

The subjective nature of these levels of service have their limitations, however they do provide an important insight in to network response and mitigation priorities on a suburb-by-suburb, and a network-by-network basis.

Based on this analysis, Sumner would be a priority for all applicable infrastructure assets, followed closely by New Brighton, South Brighton and South Shore. Lyttelton may also be considered a high priority given its expected loss of port and rail service given, and given the local and national importance of such networks and their exclusivity to this suburb. Areas of low priority include Waimairi Beach, North Beach, Ferrymead, Heathcote Valley and Mt Pleasant.

4.5 Model Interdependence

4.5.1 Model Limitations

A number of assumptions and limitations exist within components of this tsunami impact assessment model which could have a bearing on model results. Key assumptions and limitations have been categorised as to whether they would result in the model output (i.e. probability of damage or exceeding a damage state) being over-estimated, under-estimated, or having negligible impacts on model results and consequently levels of service (Table 4.3). These values were determined subjectively based on the review of literature presented in Chapter 2, with particular regard to impact assessment limitations.

Table 4.3: Assumptions and limitations of tsunami impact assessment models and likely implications to outputs

Assumption/limitation	**Implication for Model**		
	Under estimation	*Over estimation*	*Negligible*
Models based on damage matrix do not determine damage state		■	
Construction standards not considered	■	■	
Other hazard metrics not considered (e.g. velocity & debris impacts)	■		
'Road use' is not equivalent to 'construction type' for roads model	■	■	
Qualitative vulnerability metrics		■	
Broad inundation depth bins		■	
Use of 'generic' fragility curves	■	■	
Low volumes of literature/observations for some qualitative damage probabilities		■	■
Fragility curves encompass assets exposed to prior earthquake impacts		■	
Inundation model assumes static topography	■		
Levels of service do not consider network interdependency and cascading damage	■		
Levels of service do not take all infrastructural assets into account	■		
Subjective levels of service	■		

4.5.2 Model Refinement

This model could be refined by

- Quantitative vulnerability metrics for all infrastructural assets
- Developing fragility curves based upon construction standards for New Zealand assets
- Developing fragility curves that define variations in vulnerability for different asset construction types
- Inventories for more infrastructural assets (electrical cables and substations should be a priority)
- Modelling different inundation scenarios
- Extending the assessment to include regions outside of the Christchurch metropolitan area

The tsunami impact models presented here have been designed to allow for the easy integration of other infrastructural assets, hazard models, and locations. It is also recommended that further research into tsunami fragility curve development for infrastructure be used to replace current qualitative methods.

4.6 Implications for Christchurch

This section discusses the potential implications this research has for response and recovery operations in Christchurch city based on modelled impacts to infrastructure. Implications for both inundated and non-inundated areas are discussed. A discussion on the implications for Christchurch's ongoing recovery as well as prioritisation of risk treatment strategies are then discussed.

4.6.1 Network Interdependence

Access to eastern suburbs could be restricted following the given tsunami scenario. This may occur due to damaged roads and bridges or extensive debris coverage throughout the inundation zone. Consequently, this may hinder response and recovery efforts. Moncks Bay, Sumner and South Shore (see Appendix 7.4) could be particularly impacted given their presently limited access routes, which could be further limited following tsunami damage. Taylors Mistake beach (south of Sumner) could become extremely isolated given its location.

Asset data were not available for electricity networks for the present research (but could be easily implemented in the future). However, based on fragility curves developed by Horspool & Fraser (2015), damage to the electricity network could likely occur, including overhead cables and substations. In these curves, at 4 m of tsunami inundation a 10 m pole has a 0.6 probability of exceeding DS2, (where it would at least require repairs). An outdoor substation has a 0.8 probability of reaching or exceeding minor damage (DS1), which would require shut down and repairs, at just 1 m tsunami inundation. Given that areas like Sumner could experience >4 m inundation in the present scenario, damage to the Christchurch electricity network could be expected. The loss of electrical services could subsequently have significant implications for response and recovery operations following a damaging tsunami. In the case of electricity loss this is often remedied by use of mobile generators, although these are then dependant on fuel supply (mentioned further below). Recovery of the electricity network itself could again be hindered by network interdependence including access restrictions and other infrastructure service losses.

Building on the above point, damage to Lyttelton wharves (Figure 4.5) could also be a significant hindrance to response and recovery efforts following a damaging tsunami. This is especially important given that this scenario is unlikely to be a local event. Coastal roads, rails and ports could feasibly be damaged elsewhere along the East Coast of the South Island. Lyttelton also has national importance to South Island mining, agricultural and manufacturing exports, many of which are sent through the port. Irrespective of response and recovery actions, supplies to Christchurch and possibly the South Island would be limited as a result of wharf damage (e.g. fuel shortages). One other impact not considered in the assessment of Lyttelton Port is possible changes to harbour bathymetry following a tsunami. Dredging may be required if large vessel access routes have shallowed (Horspool & Fraser 2015). Following the 2011 'Tohoku' earthquake tsunami in Japan, debris had to be cleared from harbours and ports to allow access for vessels (Sagara & Ishiwatari 2012). This could likely be the case in Lyttelton with the given scenario, however the harbour could feasibly remain navigable. There is a lower debris potential given the harbour's steep slopes and comparatively sparse built environment. Lyttelton Township is not expected to lose any services outside of the port in this scenario (Table 4.2). The most direct impact on the community may likely be a temporary or permanent loss of work for port employees. In saying this, the recovery and rebuild phases of a disaster often increase opportunities for jobs in other business sectors as well as recovery work. This was evident in parts of Christchurch following the 2011-2012 'Canterbury earthquake sequence' (Stevenson et al. 2011). Another point to consider is that given the probabilities of damage to the fuel storage tanks (Figure 4.5), loss of service is not expected from the Lyttelton 'tank farm'. However any damage has the potential to trigger fires. This could have significant impacts on the surrounding infrastructure and may be difficult to contain with limited firefighting access following a tsunami.

Tsunami impacts to infrastructure could cascade into areas outside of the inundation zone. One such impact that can affect infrastructure after a tsunami is silt dispersion. Based on the literature review and post-event field observations, sea breezes can remobilise tsunami deposits and carry them farther inland. Also the loss of a wastewater pumping station could result in the bypass of treatment facilities for that specific catchment. This would however not likely effect wastewater disposal in other catchments, provided the wastewater treatment plant (Figure 4.6) remains operational (Centre for Advanced Engineering 1997; Snyder-Bishop, K, 2015, pers comm., 17 November). As mentioned previously the Christchurch city wastewater treatment plant is not exposed in the given tsunami scenario other than its eastern most stop-banks.

Not considered in the present research are the conditions preceding and following a tsunami event. Inland flooding due to damage of stormwater networks and outflows could be exacerbated by adverse weather conditions flushing greater volumes of tsunami deposits into the network. Water being drained eastward from western Christchurch may be restricted due to network blockages. This could result in flooding at various locations. Changes to surface flow patterns could also occur following tsunami soil erosion and deposition, which may also result in surface flooding. Damage to buildings could also result in unrestricted flows of potable water from private properties. Significant occurrences of this can result in lower water pressure for other parts of the network (Snyder-Bishop, K, 2015, pers comm., 17 November) and also add to surface flooding within the impacted zones. If extensive, a loss of pressure can result in the intrusion of untreated water, including sea water, wastewater and stormwater, contaminating larger sections of pipe networks. Defining the cascading effects of network losses outside of the inundation zones, in this scenario, would require a network interdependency analysis and further tsunami impact modelling.

4.6.2 Ongoing Recovery

Christchurch was severely impacted by the 2011 - 2016 'Canterbury earthquake sequence' and many infrastructure networks required repair and renewal that are ongoing today. Much of this damage occurred in the eastern suburbs (see Figure 1.10) which are exposed to the given tsunami scenario presented in this research. There are areas within this inundation zone which had loss of services following the 2011 Canterbury earthquake sequence. Affected residents and businesses may struggle to cope with the loss of lifeline services once more under the present scenario (Stevenson et al. 2011). The economic cost of infrastructure repairs could be high given the potentially national scope of a tsunami event. On top of that, skilled network repairers may be spread thinly during the response and recovery phase of an event like this. It could feasibly take many more years to get services back to their pre-event standard. One positive implication of this is that job opportunities can increase for recovery workers, providing an economic boost for impacted areas (Stevenson et al. 2011).

4.6.3 Risk Treatment Prioritisation

The present research provides an opportunity for emergency managers, planners and lifelines group managers to reduce the impacts of a damaging tsunami on infrastructure, with some degree of confidence in terms of where priorities may lie. Sumner could be considered a high priority for all assets, based on the concentration of higher damage probabilities in the impact models. The suburb also has the highest concentration of people within the inundation zone, with approximately 3,345 inhabitants (Statistics New Zealand 2013). Lyttelton Port may also be considered a priority for mitigation, given the every-day and post-event importance of its operation, as discussed above.

Tsunami risk reduction should also consider that there will be a number of challenges to be overcome before some areas can be re-occupied after a tsunami including:

- reinstatement of critical infrastructure;
- cleaning and repair of roads to provide access;
- assessment of what areas are beyond repair;
- disposal of debris and other tsunami deposits

4.7 Response and Mitigation Options

Appendix 7.7 presents a summary of response and mitigation options. This has been designed as a follow-on from the damage matrix developed in Chapter 2 (Appendix 7.3). It provides a response and mitigation option for each damage style, determined for every asset in the preceding damage matrix. The index was completed by conducting a further review of relevant literature and post-event field observations. These are not specific to Christchurch city, and thus could be applied globally. A high level summary for risk treatment of Christchurch city infrastructure is not included, as the mitigation options for tsunami impacts on infrastructure are vast (Appendix 7.7). The assessment of appropriate risk treatment, within the risk management framework (Figure 1.1) should include a detailed cost benefit analysis (Power 2013), in order to determine appropriate tsunami mitigation techniques, which falls outside the scope of the present research.

4.8 Summary

This chapter presents the results of a tsunami impact assessment for Christchurch city infrastructure, having already established methods and data requirements in previous chapters. Damage probability maps and levels of service are presented for each available infrastructural network. The results are critically discussed including research limitations and study implications. Finally a response and mitigation index is presented for tsunami impacts on infrastructure.

Chapter 5

Conclusions and Recommendations

5.1 Summary and Conclusions

The purpose of this thesis, as outlined in Chapter 1, is to assess the tsunami impacts on Christchurch city infrastructure with the aim of providing information that will help local emergency managers, planners in the reduction of tsunami impacts. The thesis also informs infrastructure managers.

In order to meet research objectives, systematic reviews of published literature and post-event survey observations were conducted for tsunami damage styles, tsunami impact assessments, tsunami impacts on infrastructure and tsunami response and mitigation options for infrastructure.

Tsunami were found to have four key styles of damage in Chapter 1: inundation and contamination; hydrodynamic forces; debris impacts; and soil instability. A review of tsunami literature in Section 2.2 found that an impact assessment process is appropriate to implement for tsunami. Consequently hazard, exposure and vulnerability demand parameters were reviewed for the purpose of modelling tsunami impacts on Christchurch city infrastructure. However, the availability of locally relevant resources has been identified as a limiting factor in past tsunami impact assessments and for this research. In an effort to partially address an absence of tsunami vulnerability metrics for infrastructure, prior tsunami impacts on infrastructure were reviewed and summarised within a tsunami damage matrix (Appendix 7.3). The reviewed methods from Chapter 2 were used to implement an impact assessment process for tsunami impacts on infrastructure in Chapter 4, with both readily available resources and those synthesised from the present research. This included the tsunami damage matrix (Chapter 2; Appendix 7.3) and an analysis of Japanese road and bridge tsunami vulnerability (Chapter 3). To do this a credible tsunami impact model for Christchurch city infrastructure was run based on existing hazard models (Appendix 7.1) for a hypothetical tsunami scenario, with results presented in Chapter 4.

It is concluded, based on the findings of this research (Chapter 4), that exposed areas of Christchurch city are likely to experience significant damage for all infrastructural sectors in the given tsunami scenario. The scenario used (Appendix 7.1) represents an extreme tsunami event for Christchurch, thus the results potentially represent the maximum (worst-case) tsunami impacts on infrastructure. Some exposed areas of Christchurch are likely to experience significant damage across all infrastructural sectors, the most widespread of which are in the suburb of Sumner. This research also suggests that transport infrastructure, notably roads and bridges, are likely to perform well in the given tsunami scenario, with low probabilities of significant damage occurring, the highest of which is <0.4, at approximately 6 m inundation depth. This is despite roads having the highest exposure of any above-ground infrastructure (second to buried wastewater pipes). Cellular towers, wharves, wastewater pumping stations and open stormwater channels were found to be the most likely infrastructural assets to incur damage (likelihood of damage = high) in the given tsunami scenario, although no measure of damage intensity is prescribed. Notably absent from the impact assessment were electricity assets (e.g. cables and substations) due to limitations with data accessibility.

The findings of a tsunami impact assessment on Christchurch city infrastructure were used to assign aggregated levels of service for each exposed Christchurch city suburb. It was found that Sumner is likely to experience loss of service from all assessed infrastructure networks for this scenario, while New Brighton, South Brighton, South Shore and Moncks Bay were all assessed as likely to lose all but wireless telecommunication services. Bexley and Rawhiti are also likely to lose service from some infrastructure networks. It was found that Lyttelton is unlikely to lose service of infrastructure from any of those mentioned above, however rail and wharf assets are both likely to experience a loss of service for the given tsunami scenario.

Some areas of Christchurch are assessed as a priority for tsunami risk management, including the mitigation options found in Appendix 7.7. This is based on the findings from the tsunami impact assessment on infrastructure and the assessed likely levels of service (Section 4.4). The areas of highest priority are the suburbs of Sumner (all infrastructure) and Lyttelton (wharves and rail). Other areas of risk management prioritisation would firstly include New Brighton, South Brighton, South Shore and Moncks Bay, then secondly Bexley and Rawhiti.

The results from this research also provide lessons for other New Zealand cities and those around the world that are at risk from tsunami. Tsunami impact assessments on infrastructure can be resource- and labour-intensive, but they provide an invaluable tool for the management of tsunami impacts. The tsunami impact assessment model for Christchurch city infrastructure developed here is easily adaptable to other locations given the availability of, or ability to develop, appropriate resources. Reflections and lessons for Christchurch city beyond this research are summarised in the section below.

5.2 Recommendations

This section presents general guidelines and recommendations for assessments of tsunami impacts on infrastructure, including future research directions based on experience from this study. Also presented are specific recommendations for Christchurch city infrastructure tsunami impact assessments.

5.2.1 Assessment of Tsunami Impact on Infrastructure: General Recommendations

Effective tsunami impact assessments first require robust and accurate tsunami hazard models, whether a probabilistic or deterministic approach is implemented. It is therefore recommended that cities, or other areas of significant societal importance, develop site specific tsunami hazard models such as that presented in Appendix 7.1.

Tsunami vulnerability of infrastructure resources was identified as being limited early on in this thesis. Tsunami impact assessments on infrastructure would benefit largely from the future collection of quantitative data from experimental and field observations. Building on this point, a common causal factor for limited data is the qualitative approach used in previous post-event tsunami surveys. The standardisation of tsunami post-event field surveys would benefit tsunami impact management by providing a register of essential observational data for surveyors to collect following future tsunami events, and to ensure that a census-style survey is conducted covering all exposed assets (e.g. such as that conducted by GNS Science following the 2015 'Illapel' earthquake tsunami), not just those experiencing some degree of damage. This would provide greater quantitative resources for future impact assessments, better data to inform tsunami risk management and would potentially justify more empirical laboratory studies.

Building upon the above points, and as mentioned in Chapter 4, although a tsunami damage matrix is an acceptable substitute for vulnerability metrics in the absence of quantitative fragility functions, tsunami impact assessments on infrastructure would benefit greatly from the development of fragility curves for an increased number of infrastructural assets. With future quantitative data, or that collected by GNS Science following the 2015 'Illapel' earthquake tsunami, this will be possible. This would produce higher-resolution probabilistic tsunami impact assessments given the potential inclusion of damage state analyses and construction type differentiation of assets.

In addition to developing fragility curves for more assets, the development of vulnerability metrics incorporating more hazard intensity measures, such as flow velocity, would provide a comparison between that and inundation depth variants. This could potentially constrain more accurate/applicable vulnerability demand parameters for use in future tsunami impact models. Incorporating a degree of debris impact vulnerability would also benefit the reduction of tsunami impacts on infrastructure. The inclusion of a degree of soil instability vulnerability could similarly be implemented into a tsunami impact assessment, using a soil type ranking system or similar methods. This would require detailed site-specific soil classifications and knowledge of soil-type scour potentials.

Another recommendation to increase the resolution of vulnerability metrics, and therefore results, of a tsunami impact assessment on infrastructure, is to assign damage states for each asset in the tsunami damage matrix (Appendix 7.3). This would allow a qualitative assessment of damage level probabilities in the absence of quantitative fragility functions. This would again require further knowledge of an asset's likely level of damage for given hazard intensities (e.g. tsunami inundation depth).

It is also recommended to implement the findings of the research presented in this thesis, including methodology, results and fragility curves, into national multi-hazard impact and loss modelling tools such as RiskScape. This would allow emergency managers, planners and lifelines groups easy access to relevant tsunami impacts on infrastructure data as well as to run infrastructure impact models for specific requirements (e.g. another city or infrastructural asset type).

The most important of these recommendations is that higher resolution, and more abundant, resources are made available for effective tsunami impact assessments on infrastructure, especially with respect to tsunami vulnerability metrics for infrastructure. The impact assessment process has been proven effective within the risk analysis stage of the risk management framework and input parameters including hazard, exposure and vulnerability can be easily implemented in future studies.

5.2.2 Research Directions for Christchurch Infrastructure Tsunami Risk

The improvement of tsunami impact assessments on Christchurch city infrastructure fits within the monitoring and review stage of the risk management framework. All recommendations for tsunami impacts on infrastructure presented in the above section, are also recommended for implementation in subsequent tsunami impact assessments of Christchurch city infrastructure. Building upon recommendations already presented in the above section, other recommendations for Christchurch city impact and risk management are included below.

More assets need to be incorporated into future tsunami impact assessments on Christchurch city infrastructure. Modelling electricity and telecommunication networks, for example, may be beneficial for risk management actions given their potential post-disaster importance, likely interdependency with other infrastructural networks and their contribution to the normal operation of society.

This study focussed on impacts and levels of service immediately following a tsunami. Research into short-to-long term losses of service or cascading damage may better inform response and mitigation strategies. The level of service assignments themselves would also benefit from either expert validation or quantitative analysis.

Christchurch is still in a recovery phase following the 2011-2016 'Canterbury earthquake sequence', consequently infrastructure is being continually repaired and upgraded as a method of risk treatment to that specific hazard. Hence asset data should be regularly updated from those used in this thesis to ensure the results remain relevant. This is especially imperative for asset attribute data.

This research used a deterministic approach to model impacts on infrastructure based on a single tsunami inundation model. Modelling tsunami impacts using different inundation scenarios would test the present research as well as informing emergency managers and planners about the likely impacts associated with lower magnitude tsunami events, including local and regional source tsunami.

Extending the study to include regions outside of the area assessed in this research would also help inform tsunami risk management for Christchurch city, (e.g. transport corridors).

Building upon the assignment of levels of service presented in Chapter 4, the economic cost associated with the research findings could be calculated in subsequent studies. This may be used to quantify the tsunami impacts on infrastructure and highlight 'hotspots' of economic loss to provide a different metric of prioritisation for potential mitigation strategies including a cost benefit analysis.

6.0 References

Akiyama, M. et al., 2013. Reliability of bridges under tsunami hazards: Emphasis on the 2011 Tohoku-oki earthquake. *Earthquake Spectra*, 29(SUPPL.1), pp.S295–S314. Available at: http://www.earthquakespectra.org/doi/abs/10.1193/1.4000112.

Bell, R. et al., 2005. Survey of impacts on the Andaman coast, Southern Thailand following the great Sumatra-Andaman earthquake and tsunami of December 26, 2004. *Bulletin of the New Zealand Society for Earthquake Engineering*, 38(3), pp.123–148.

Borrero, J.C. & Goring, D.G., 2015. South American Tsunamis in Lyttelton Harbor, New Zealand. *Pure and Applied Geophysics*, 172(3-4), pp.757–772.

Centre for Advanced Engineering, 1997. *Risk and Realities: a Multi-disciplinary Approach to the Vulnerability of Lifelines to Natural Hazards* C. Hendtlass & U. O'Grady, eds., Christchurch: University of Canterbury.

Chandrasekar, N. & Ramesh, R., 2007. Tsunami Damage to the South Eastern Coast of India.

Charvet, I. et al., 2015. A multivariate generalized linear tsunami fragility model for Kesennuma City based on maximum flow depths, velocities and debris impact, with evaluation of predictive accuracy. *Natural Hazards*, 79(3), pp.2073–2099. Available at: "http://dx.doi.org/10.1007/s11069-015-1947-8.

Chen, C. & Melville, B.W., 2015. Experimental Study of Uplift Pressures on Wharf Decks Due to Tsunami Bores.

Cruz, A.M., Franchello, G. & Krausmann, E., 2009. Assessment of Tsunami Risk to an Oil Refinery in Southern Italy.

Daly, M. & Johnston, D., 2015. The genesis of volcanic risk assessment for the Auckland engineering lifelines project: 1996–2000. *Journal of Applied Volcanology*, 4(1), p.7. Available at: http://www.appliedvolc.com/content/4/1/7.

Dominey-Howes, D. et al., 2012. International Tsunami Survey Team (ITST) Post-Tsunami Survey Field Guide. , 2.

Edwards, C., 2006. Thailand lifelines after the December 2004 Great Sumatra earthquake and Indian Ocean tsunami. *Earthquake Spectra*, 22(SUPPL. 3), pp.641–659.

Eguchi, R.T. et al., 2013. HAZUS Tsunami Benchmarking, Validation and Calibration

ESRI contributors, 2015. ArcMap Desktop 10.3.

Frangopol, D.M. & Bocchini, P., 2012. Bridge network performance, maintenance and optimisation under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering*, 8(4), pp.341–356.

Fraser, S.A. et al., 2014. Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling. *Natural Hazards and Earth System Sciences Discussions*, 2(6), pp.4163–4200.

Fritz, H.M. et al., 2011. Field Survey of the 27 February 2010 Chile Tsunami. *Pure and Applied Geophysics*, 168(11), pp.1989–2010.

Fritz, H.M. et al., 2012. The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR. *Geophysical Research Letters*, 39(2), pp.1–6.

Gaurdian News and Media Limited, 2015. Chile earthquake: one million people evacuated after 8.3 magnitude quake. Available at: http://www.theguardian.com/world/live/2015/sep/17/chile-earthquake-massive-83-magnitude-tremor-strikes-santiago-live-updates.

Ghobarah, A., Saatcioglu, M. & Nistor, I., 2006. The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure. *Engineering Structures*, 28(2), pp.312–326. Available at: http://www.sciencedirect.com/science/article/pii/S0141029605003548.

Gill, D., Clough, P. & Webb, T., 2015. *Tsunami risk facing New Zealand*, Wellington.

GNS & NIWA, 2015. RiskScape Technical Documentation Wiki. Available at: https://wiki-riskscape.niwa.co.nz/index.php/RiskScape_Technical_Documentation_Wiki [Accessed March 15, 2015].

Goff, J. et al., 2006. Sri Lanka field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, 22(SUPPL. 3), pp.155–172.

Goff, J. & Chagué-Goff, C., 2012. A review of palaeo-tsunamis for the Christchurch region, New Zealand. *Quaternary Science Reviews*, 57, pp.136–156. Available at: http://dx.doi.org/10.1016/j.quascirev.2012.10.004.

Google, 2015. Google Earth Pro Desktop.

Graf, W.P., Lee, Y. & Eguchi, R.T., 2014. New Lifelines Damage and Loss Functions for Tsunami.

Hart, D.E. & Knight, G. a., 2009. Geographic Information System Assessment of Tsunami Vulnerability on a Dune Coast. *Journal of Coastal Research*, 251, pp.131–141.

Hatayama, K., 2014. Damage To Oil Storage Tanks Due To Tsunami of the Mw9 . 0 2011 Off the Pacific Coast of Tohoku , Japan.

Horspool, N.A. & Fraser, S., 2015. *An Analysis of Tsunami Impacts to Lifelines*, GNS Science Consultancy Report 2015/40.

Jin, D. & Lin, J., 2011. Managing tsunamis through early warning systems: A multidisciplinary approach. *Ocean & Coastal Management*, 54(2), pp.189–199.

Kawashima, K. & Buckle, I., 2013. Structural performance of bridges in the Tohoku-oki earthquake. *Earthquake Spectra*, 29(SUPPL.1), pp.2–12.

Kazama, M. & Noda, T., 2012. Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage). *Soils and Foundations*, 52(5), pp.780–792. Available at: http://dx.doi.org/10.1016/j.sandf.2012.11.003.

Kim, Y.J., Marshall, W. & Pal, I., 2014. Assessment of infrastructure devastated by extreme floods: a case study from Colorado, USA. *Proceedings of the ICE - Civil Engineering*, 167, pp.186–191. Available at: http://www.icevirtuallibrary.com/content/article/10.1680/cien.14.00032.

King, A. & Bell, R., 2006. *RiskScape New Zealand - A multihazard Loss Modeling Tool*, NZSEE Conference.

Koordinates contributers, 2015. Koordinates. Available at: https://koordinates.com/.

Koshimura, S., Oie, T., et al., 2009. Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia. *Coastal Engineering Journal*, 51(03), pp.243–273.

Koshimura, S., Namegaya, Y. & Yanagisawa, H., 2009. Tsunami fragility: a new measure to identify tsunami damage. *Journal of Disaster Research*, 4(6), pp.479–488.

Lane, E. et al., 2012. *Modelling coastal inundation in Christchurch and Kaiapoi from a South American tsunami using topography from after the 2011 February earthquake*,

Lane, E. et al., 2014. *Updated inundation modelling in Canterbury from a South American Tsunami*, Christchurch: National Institute of Water and Atmospheric Research.

De Lange, W.P. & Healy, T.R., 1986. New Zealand tsunamis 1840–1982. *New Zealand Journal of Geology and Geophysics*, 29(1), pp.115–134.

Marchand, M. et al., 2009. Damage and casualties modelling as part of a vulnerability assessment for tsunami hazards: a case study from Aceh, Indonesia. *Journal of Flood Risk Management*, 2(2), pp.120–131.

Mas, E. et al., 2012. Developing Tsunami fragility curves using remote sensing and survey data of the 2010 Chilean Tsunami in Dichato. *Natural Hazards and Earth System Science*, 12(8), pp.2689–2697.

Ministry of Civil Defence and Emergency Management, 2016. Excersise Tongaroa 2016. Available at: http://www.civildefence.govt.nz/cdem-sector/exercises/exercisetangaroa2016/ [Accessed February 16, 2016].

MLIT, 2012. Archive of the Great East Japan Earthquake Tsunami disaster urban reconstruction assistance survey. Available at: http://fukkou.csis.u-tokyo.ac.jp/ [Accessed June 1, 2015].

MLIT, 2013. MLIT. Available at: http://www.mlit.go.jp/en/index.html [Accessed December 12, 2015].

Mulligan, M. & Nadarajah, Y., 2011. Lessons from Indian Ocean tsunami disaster still to be learnt. *International Journal of Disaster Resilience in the Built Environment*, 2(1), p.null. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/ijdrbe.2011.43502aab.001.

Naito, C. et al., 2014. Procedure for Site Assessment of the Potential for Tsunami Debris Impact. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 140(2), pp.223–232. Available at: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29WW.1943-5460.0000222.

Nakanishi, H., Black, J. & Matsuo, K., 2014. Disaster resilience in transportation: Japan earthquake and tsunami 2011. *International Journal of Disaster Resilience in the Built Environment*, 5(4), pp.341–361. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/IJDRBE-12-2012-0039.

National Oceanic and Atmospheric Administration, 2015. NOAA. Available at: http://www.noaa.gov/.

NIWA, 2014. *RiskScape Tsunami Fragility Project*,

Okal, E. a. et al., 2010. Field Survey of the Samoa Tsunami of 29 September 2009. *Seismological Research Letters*, 81(4), pp.577–591.

OpenStreetMap contributors, 2015. Open Street Map. Available at: https://www.openstreetmap.org [Accessed June 15, 2015].

Palliyaguru, R. & Amaratunga, D., 2008. Managing disaster risks through quality infrastructure and vice versa. *Structural Survey*, 26(5), pp.426–434. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/02630800810922766.

Papathoma, M. & Dominey-Howes, D., 2003. Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. *Natural Hazards and Earth System Science*, 3(6), pp.733–747.

PIANC Working Group 53, 2009. Mitigation of tsunami disasters in ports. *Group*, p.114.

Porter, K., *A Beginner's Guide to Fragility, Vulnerability, and Risk*,

Power, W., 2013. *Review of Tsunami Hazard in New Zealand (Update 2013)*.

Prasetya, G. et al., 2012. Debris dispersal modeling for the great Sumatra Tsunamis on Banda Aceh and surrounding waters. *Natural hazards*, 60(3), pp.1167–1188.

Reese, S. et al., 2011. Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. *Earth-Science Reviews*, 107(1-2), pp.156–173.

Reese, S., Tool 3 . 2 : Using RiskScape for Risk Analysis Author. Available at: https://www.niwa.co.nz/sites/niwa.co.nz/files/tool_3.2_using_riskscape.pdf.

Saatcioglu, M., 2007. Biophysical and Socio-Economic Dimensions of Tsunami Damage Performance of Structures Affected by the 2004 Sumatra Tsunami in Thailand and Indonesia.

Sagara, J. & Ishiwatari, M., 2012. Infrastructure Rehabilitation. *Knowledge Note*, 1, pp.1–14.

Scawthorn, C. et al., 2006. Performance of lifelines in Banda Aceh, Indonesia, during the December 2004 Great Sumatra earthquake and tsunami. *Earthquake Spectra*, 22(SUPPL. 3), pp.511–544.

Scheele, F., 2016. *Impact assessment of a far-field tsunami scenario for building damage and habitability in Christchurch*. University of Canterbury.

Schmidt, J. et al., 2011. Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Natural Hazards*, 58(3), pp.1169–1192.

Shoji, G. & Moriyama, T., 2007. Evaluation of the Structural Fragility of a Bridge. *Journal of Natural Disaster Science*, 29(2), pp.73–81.

Standards New Zealand, 2009. *Risk Management - principles and guidlines*, ISO31000

Stevenson, J.R. et al., 2011. Preliminary observations of the impacts the 22 February Christchurch earthquake had on organisations and the economy: A report from the field (22 February - 22 March 2011). *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(2), pp.65–76.

Suppasri, A. et al., 2013. Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. *Natural Hazards*, 66(2), pp.319–341.

Sword-Daniels, V. et al., 2014. Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience. *Geological Society, London, Memoirs*, 39, pp.471–488. Available at: http://mem.lyellcollection.org/content/39/1/471.abstract.

Thywissen, K., 2006. *Components of risk. A comparative glossary. Studies of the University: Research, Counsel, Education-Publication Series of UNU-EHS*, USGS, 2015. U.S. GeologicalSurvey. Available at: http://www.usgs.gov/ [Accessed April 23, 2015].

Wilson, T., Daly, M. & Johnston, J., 2009. *Review of impacts of volcanic ash on electricity distribution systems, broadcasting and communication networks*, Auckland.

Wright, K.C. & Cousins, W.J., 2014. *Evacuation Numbers and Current Evacuation Planning in Wellington Region for a Tsunami Generated by a Large Hikurangi Subduction Zone Earthquake*,

Yeh, H., Sato, S. & Tajima, Y., 2013. The 11 March 2011 East Japan Earthquake and Tsunami: Tsunami Effects on Coastal Infrastructure and Buildings. *Pure and Applied Geophysics*, 170(6-8), pp.1019–1031.

7.0 APPENDICES

Appendix 7.1: Christchurch Tsunami Hazard Models

Lane et al. (2014) have modelled the tsunami hazard for Christchurch city using a mathematical equation of fluid motion, based on a Mw 9.485 Peru subduction zone event. It represents the hazard at a 2,500 year return period. This updated tsunami model represents the best estimate of far-field tsunami inundation of the Christchurch coast to date and indicates that Christchurch city and Lyttelton Harbour would experience the worst of the inundation in Canterbury. The largest wave arrival is assumed to coincide with mean high water spring tide (MHWS) in this model. Areas which experience the highest levels of inundation (>2.5m) include New Brighton, South Shore, Redcliffs, Sumner, Taylors Mistake and low lying areas of Lyttelton Port (Figures 7.1 and 7.2). The highest flow velocities are concentrated around the Avon-Heathcote mouth, including South Shore, Ferrymead and Sumner, with velocities greater than 5.1m/s, which are also seen at the entrance of the Lyttelton Port. New Brighton sees velocities of up to 4m/s, but most of the other inundated areas experience velocities below 2 m/s (Figure 7.3 and 7.4).

The research presented in this thesis uses what has been considered a credible worst case scenario for Christchurch city from 4 possible source event variations. The technical details of the chosen scenario model are presented below (GNS & NIWA 2015).

Model name: Canterbury Tsunami Model 1 in 2,500 year return period from South Peru - North Canterbury (Scenario 2)

Author: Dr Emily Lane

Organisation: National Institute of Water and Atmospheric Research

Date: August 2014

Description: Inundation model of coastal locations in Canterbury by a tsunami generated from an earthquake off-shore of South Peru with a magnitude Mw 9.485. This comes from the deaggregation of tsunami hazard with a return period of 1:2,500 years for Christchurch city as calculated in Power (2013).

Model: Far-field modelling:

Gerris: Gerris is based on a quad-tree grid and is able to adaptively refine specified areas to ensure error is kept below a given level. Gerris was used to model the wave from source to approximately 197 E, the boundary with the RiCOM inundation grids.

RiCOM: The RiCOM hydrodynamics model uses an irregular, unstructured, finite element grid which allows high resolution and refinement in areas of inundation around the coast, and improves numerical accuracy by controlling grid size relative to water depth. The grids used were originally made for several earlier inundation studies for ECAN.

Input Data: LIDAR supplied by ECAN (post February 2011 earthquake for Christchurch and Kaiapoi), digitised charts, NIWA bathymetry. Post-earthquake bathymetry of the Avon-Heathcote Estuary. Avon stop banks, Waimakariri stop banks and Sumner sea wall design heights and positions.

Model Area: The grid extends from the east coast of New Zealand to 197 E. Areas of interest for inundation modelling have increased resolution such as Christchurch and Banks Peninsula, which includes Christchurch city, Lyttelton Harbour coastal margin and Akaroa Harbour coastal margin.

Additional Source Event Information: Scenario 2 (40 m slip; 1,500 km by 150 km):

- Location: x = 286.608056°E y = -17.418918°N
- Depth = 25000m
- Strike = 307° dip = 10° rake = 90°
- Length = 600e3m width = 150e3m U = 40m

Coordinate System: New Zealand Transverse Mercator

Output Format: Ascii raster grid (regular), GIS Maps

Model Limitations: Spatial resolution is variable but in the regions of interest for inundation is around 10-15 m. Open ocean at the edges of the grid have resolution as coarse as several kilometres and resolution grades smoothly between these. Variable, finest resolution of modelling around 10 m. Ascii raster files should be used at a scale of 1:25,000 at most. Tide not accounted for except as static level, erosion/accretion of land not considered, bare earth LiDAR used, constant land friction assumed, uncertainties in incoming wave train source. Climate change not considered.

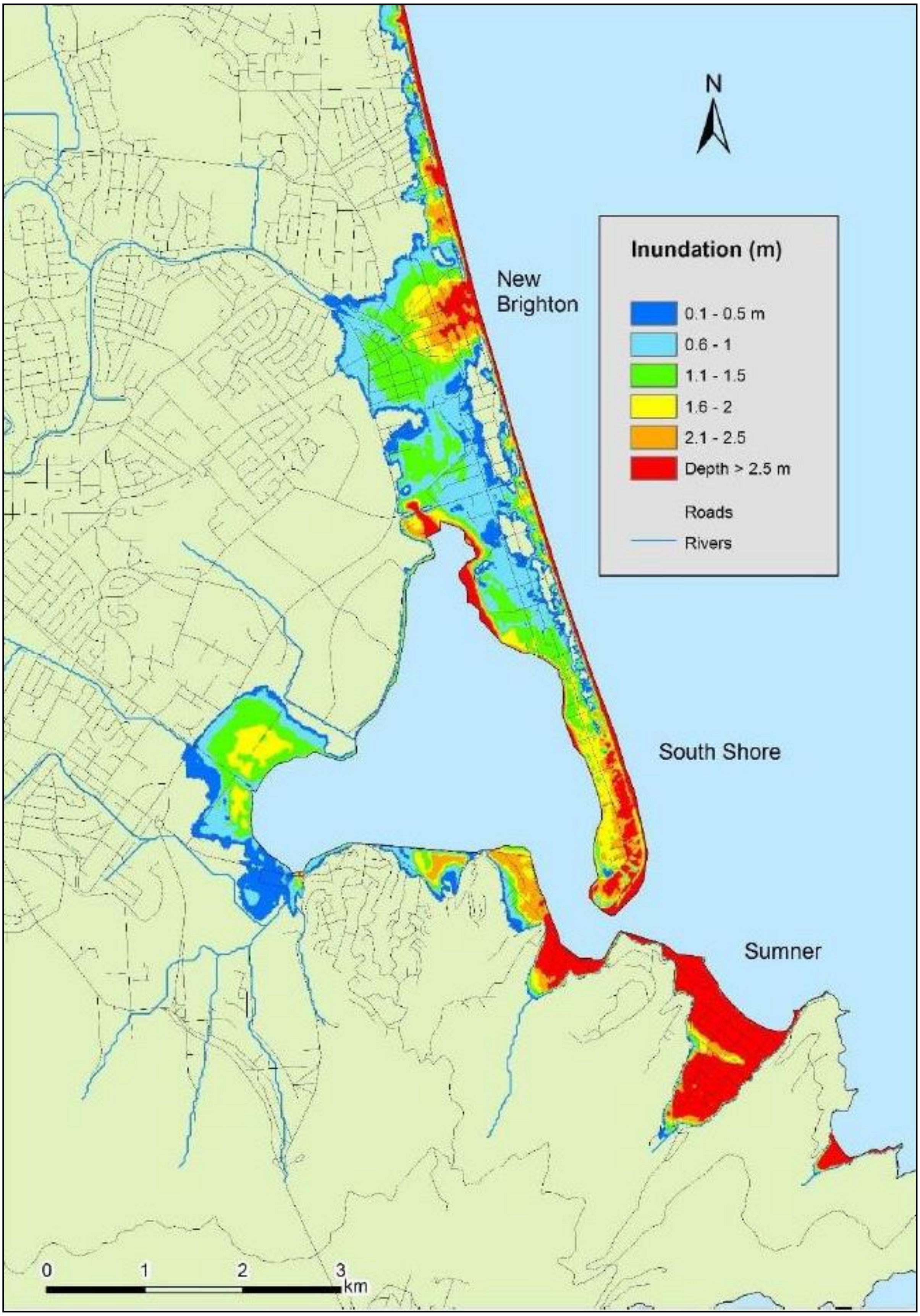

Figure 7.1: Maximum inundation depth for Christchurch assuming the largest wave arrived at MHWS.

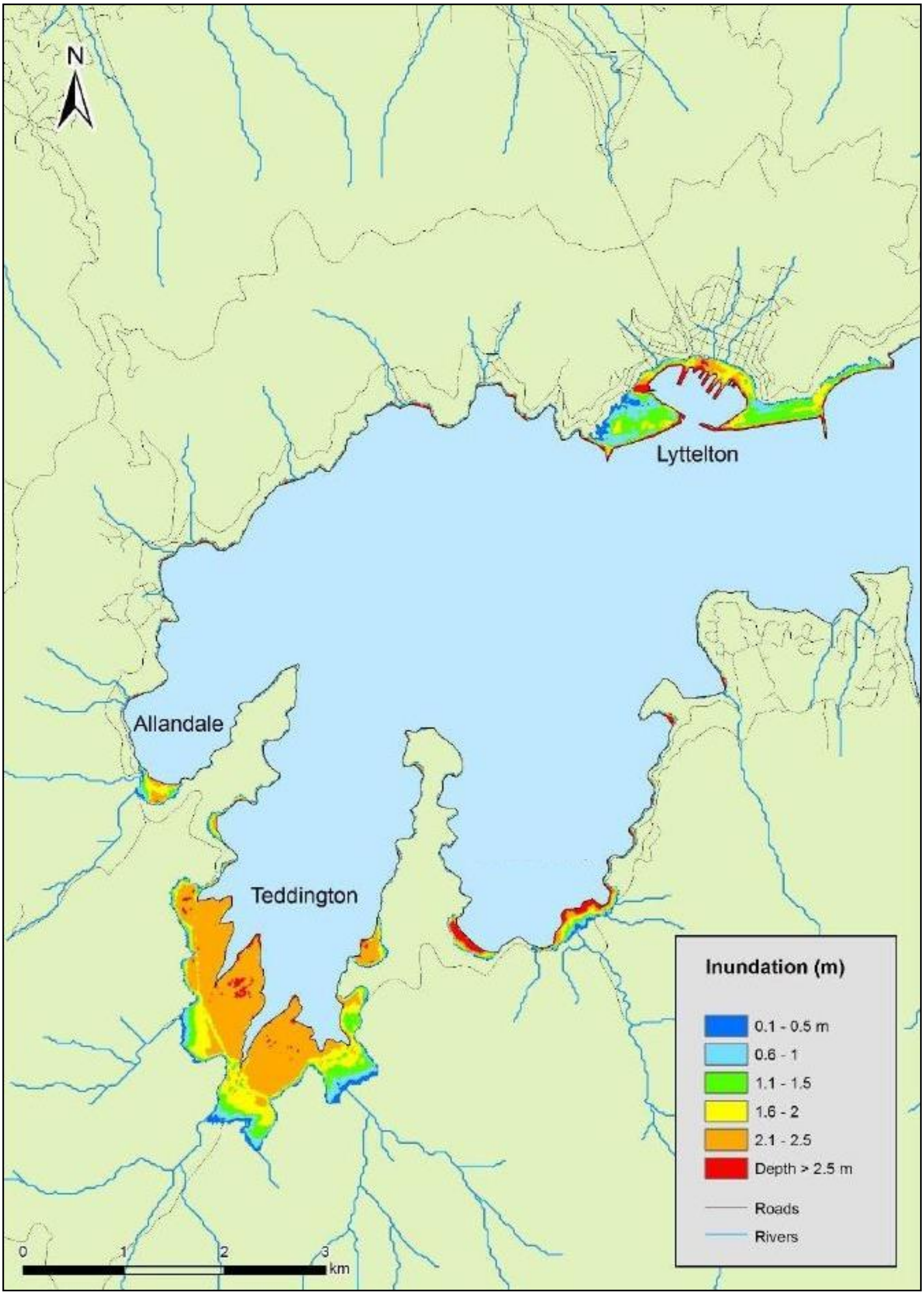

Figure 7.2: Maximum inundation depth for Lyttelton Harbour coastal margin assuming the largest wave arrived at MHWS. Inundation depths are only shown for inundated land (Lane et al. 2014)

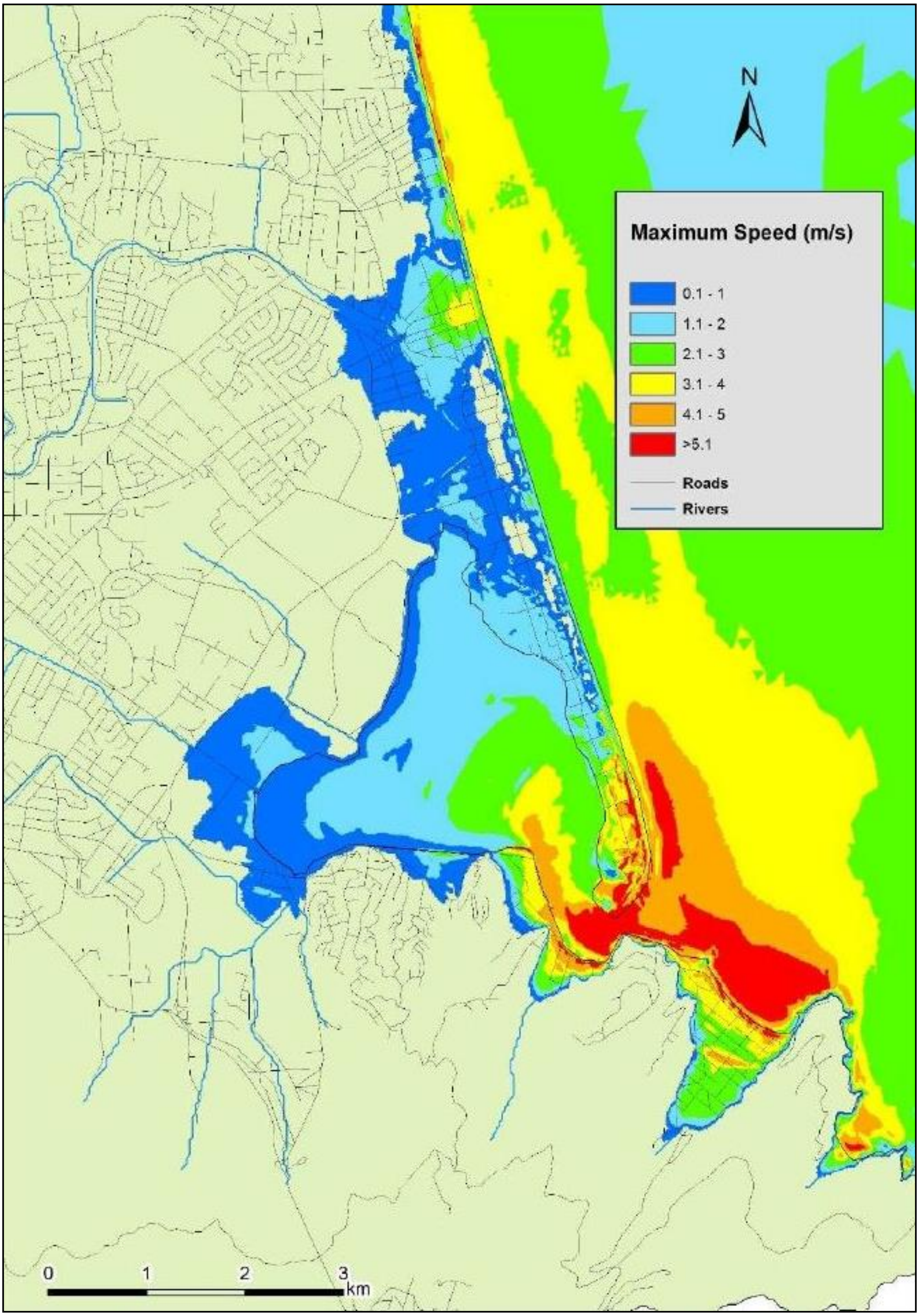

Figure 7.3: Maximum flow speed for Christchurch assuming the largest wave arrived at MHWS. Flow speeds are over 5 m/s in many areas near the Avon-Heathcote mouth (Lane et al. 2014)

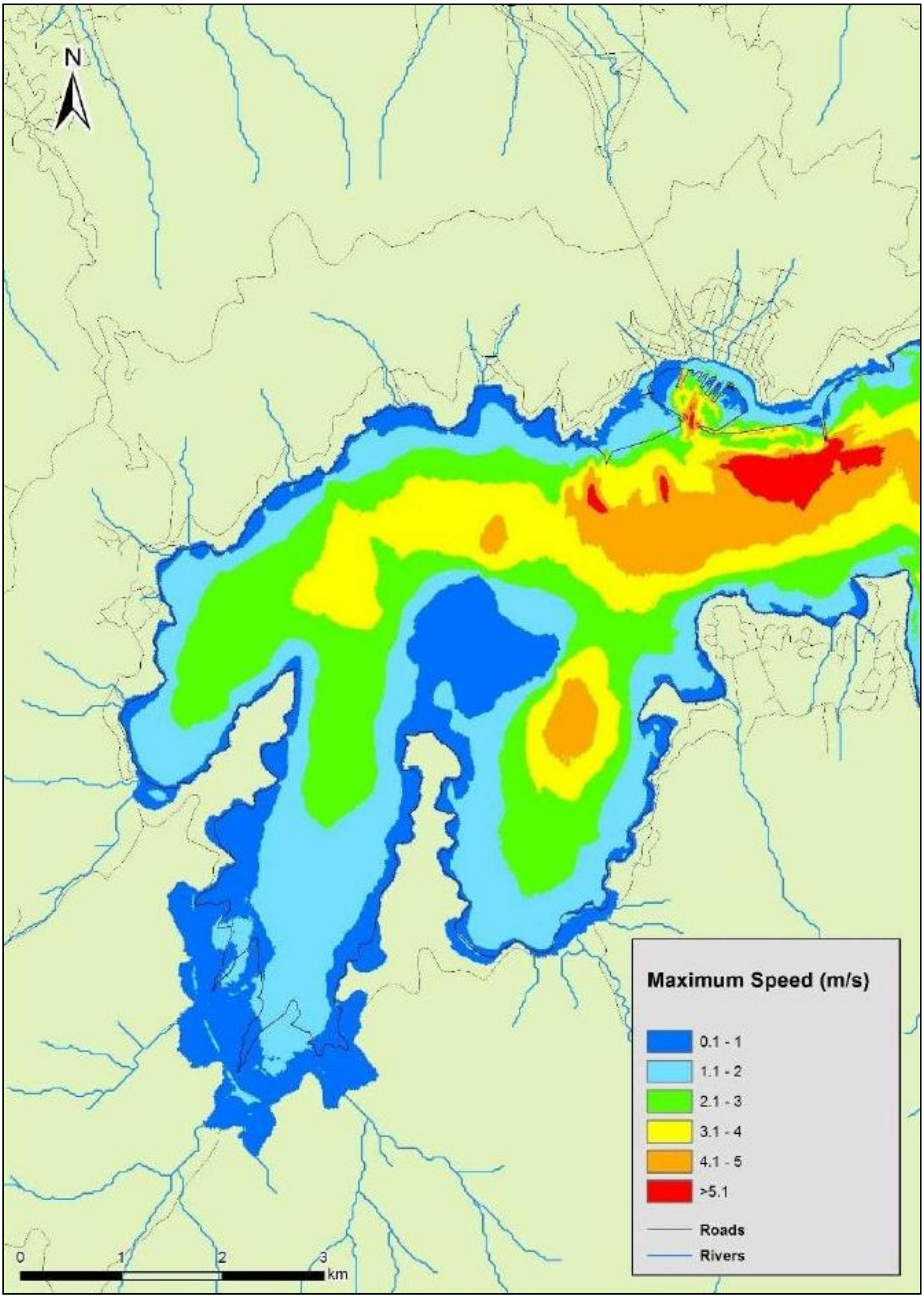

Figure 7.4: Maximum flow speed for Lyttelton Harbour coastal margin assuming the largest wave arrived at MHWS (Lane et al. 2014)

Appendix 7.2: Christchurch Coastal Dune Topography

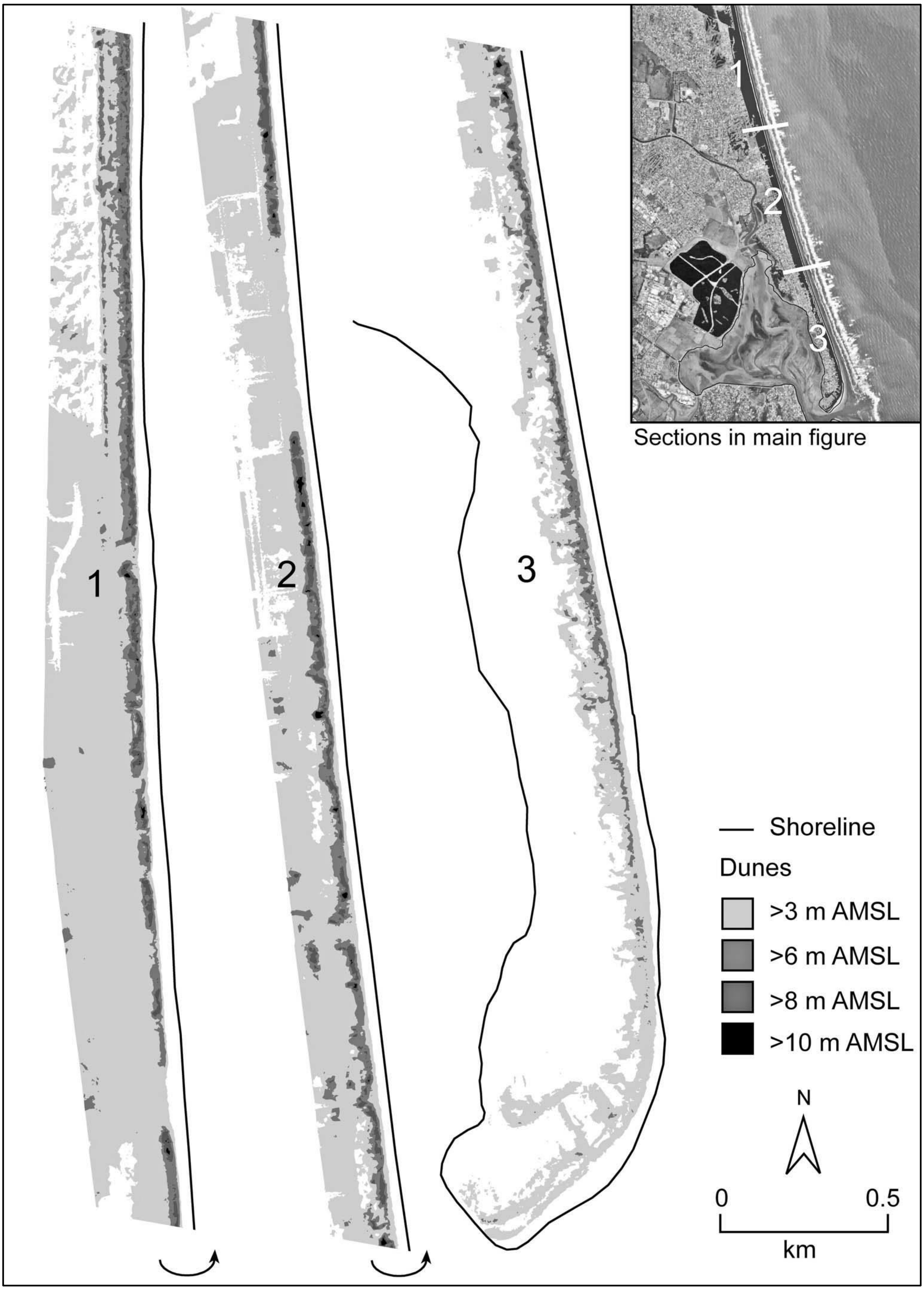

Figure 7.5: Planform cross sections of Christchurch dune coast topography (Hart & Knight 2009)

Appendix 7.3: Tsunami Damage Matrix

Infrastructural Asset	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality	Sources
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type		
Transportation								
Roads								
Pavement	Low	Silt and light debris coverage, ponding	Medium	Debris & sediment coverage, scour of weak base materials, removal of signage and markings, ponding	Medium-High	Debris strikes , scour of base materials, lifting of carriage-way, removal of barriers and signage, cracking of pavement, liquefaction of base materials, ponding, debris and sediment coverage	High	(Horspool & Fraser 2015; Unjoh 2012; Suppasri, Mas & Imamura 2013; Edwards 2006; Auckland Engineering Lifelines 2014; AON Benfield 2011; Ghobarah et al. 2006; Bell et al. 2005; Francis 2006; Kazama & Noda 2012; Lekkas 2011; Kim et al. 2014; Yeh et al. 2013; Okal et al. 2010; Eguchi et al. 2013; Tang & Edwards 2012; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)
Bridges	Negligible-Low	Superficial debris strikes	Medium	Some bank erosion, superficial debris strikes , sediment deposition, scour of footings, corrosion, washout of light timber structures	High	Debris and sediment deposition, erosion of adjoining banks, loss of signage and markings, side barriers bent or sheared, debris strikes, scour of footings, aggradation of waterway, widening of waterway separation of deck from footings, lateral distortion of super structure, separation of girders, washout of superstructure, corrosion, loss of utilities across bridge	High	(Bell et al. 2005; Evans & McGhie 2011; Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; University of Hawaii 2015; Kim et al. 2014; Saatcioglu 2007; LRFD 2010; Number et al. n.d.; Eguchi et al. 2013; Tang & Edwards 2012; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Edwards 2006; Frangopol & Bocchini 2012; Kosa 2012; Akiyama et al. 2013; AON Benfield 2011; Auckland Engineering Lifelines 2014; Francis 2006; Ghobarah et al. 2006; Iemura et al. 2005; Kazama & Noda 2012; Lekkas 2011)
Lighting	Low	Damage to electrical components	Medium-High	Debris strikes, inundation of electrical components, tilting or shearing of supports	High	Complete washout, Debris strikes , inundation of electrical components, tilting or shearing of supports	Low	(Horspool & Fraser 2015; Francis 2006; Kazama & Noda 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Vehicles	Low	Damage to electrical components	High	electrical short, floating, debris strikes , impact damage	High	Electrical short, floating, debris strikes , impact damage	Low	(Suppasri, Mas & Imamura 2013; Tomita et al. 2011; Nakanishi et al. 2014; Okal et al. 2010; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)
Rail								
Tracks	Low	Sediment deposition, scour of ballast	Medium-High	Scour of ballast, debris and sediment deposition, disruption to signage and lighting	High	Scour of ballast, debris and sediment deposition, loss of signage and lighting, distortion, washout of track	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Goff et al. 2006; Francis 2006; Lekkas 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005)

	Stations/Depots	Low	Water damage to interiors	High	Water damage to interiors wall washout, short circuiting of electrical components and machinery, corrosion, debris strikes	High	Water damage to interiors, wall collapse, short circuiting of electrical components and machinery, corrosion, debris strikes, washout	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Tang & Edwards 2012; Reese et al. 2011; American Society of Civil Engineers 2005)
	Bridges	Low	Superficial debris strikes	Medium	Some bank erosion, superficial debris strikes , sediment deposition, scour of footings, corrosion, washout of light timber structures	High	Debris and sediment deposition, erosion of adjoining banks, loss of signage and markings, side barriers bent or sheared, debris strikes, scour of footings, aggradation of waterway, widening of waterway separation of deck from footings, lateral distortion of super structure, separation of girders, washout of superstructure, corrosion, loss of utilities across bridge	Medium	(Bell et al. 2005; Evans & McGhie 2011; Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; University of Hawaii 2015; Kim et al. 2014; Saatcioglu 2007; LRFD 2010; Number et al. n.d.; Eguchi et al. 2013; Tang & Edwards 2012; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Edwards 2006; Frangopol & Bocchini 2012; Kosa 2012; Akiyama et al. 2013; AON Benfield 2011; Auckland Engineering Lifelines 2014; Francis 2006; Ghobarah et al. 2006; Iemura et al. 2005; Kazama & Noda 2012; Lekkas 2011)
	Overhead lines	Low	Scour of support foundations, shorting of low lying electrical equipment	High	Scour of support foundations, distortion of supports, collapse, debris strikes, shorting of low lying electrical equipment	High	Scour of support foundation, distortion of supports, collapse, short circuiting, debris strikes , washout	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Francis 2006; Kazama & Noda 2012)
	Trains	Negligible	Negligible	Low - High	Derailment, debris strikes, floating, impact damage	High	Derailment, debris strikes, floating, impact damage	Low	(Horspool & Fraser 2015; AON Benfield 2011; Goff et al. 2006; Kazama & Noda 2012; American Society of Civil Engineers 2005)
<u>Ports</u>	Wharves and piers	Negligible-Low	Debris strikes, scour of foundations	Medium	Sediment and debris deposition, debris strikes, scour of seabed, debris in waterways, scour of foundations	High	Aggradation/erosion of sea bed, separation of deck slabs from footings, removal of concrete blocks, subsidence, collapse, complete washout, debris in waterways	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Tomita et al. 2011; Evans & McGhie 2011; Auckland Engineering Lifelines 2014; Bell et al. 2005; Francis 2006; Kazama & Noda 2012; Lekkas 2011; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Borrero et al. 2015; Borrero & Goring 2015; Lynett et al. 2014)
	Buildings	Low-Medium	Water damage to interiors & stored goods	High	Water damage to interiors & stored goods, short circuiting of electrical components, washout	High	Water damage to interiors & stored goods, short circuiting of electrical components, washout	High	(Horspool & Fraser 2015; Evans & McGhie 2011; Auckland Engineering Lifelines 2014; Kazama & Noda 2012; Lekkas 2011; Reese et al. 2011; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)
	Plant Machinery	Low	Water damage to electrical components	High	Water damage to electrical components, debris strikes	High	Water damage to electrical components, debris strikes, washout	Medium	(Horspool & Fraser 2015; Auckland Engineering Lifelines 2014; Bell et al. 2005; Graf et al. 2014; Kazama & Noda 2012; American Society of Civil Engineers 2005)
	Vessels	Negligible-Low	Broken moorings, debris strikes, impact damage	Medium-High	Broken moorings, debris damage, impact damage, floated inland	High	Broken moorings, debris damage, impact damage, floated inland, capsized, submerged	Low	(Horspool & Fraser 2015; Tomita et al. 2011; Bell et al. 2005; Cruz et al. 2009; Kazama & Noda 2012; Lekkas 2011; Fritz et al. 2011; Kurian et al. 2007; Saatcioglu 2007; Leone et al. 2011; Tang & Edwards 2012; Scawthorn et al. 2006; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)

Containers	Negligible	Negligible	Medium	Floating of container, impact damage, debris strikes, water & impact damage to goods, dangerous goods exposed	High	Floating of container, impact damage, debris strikes, water & impact damage to goods, dangerous goods exposed, distorted, crushed	Low	(Horspool & Fraser 2015; Tomita et al. 2011; Cruz et al. 2009; Kazama & Noda 2012; Lekkas 2011; Fritz et al. 2011; Tang & Edwards 2012; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)
Airports								
Runway	Low	Silt & light debris coverage, ponding, shorting of low lying electronic components	High	Damage to lighting, debris coverage, ponding, shorting of electronic components	High	Damage to lighting, debris coverage, ponding, shorting of electronic components	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; McClelland 2011; AON Benfield 2011; Bell et al. 2005; Tang & Edwards 2012; American Society of Civil Engineers 2005)
Buildings	Low	Silt infiltration, water damage to interiors	High	Silt infiltration, water damage to interiors, wall washout, scour of foundations	High	Debris strikes, water damage to interiors, structural collapse, scour of foundations, wall washout, complete washout,	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Suppasri, Mas & Imamura 2013; AON Benfield 2011; Francis 2006; Tang & Edwards 2012; Reese et al. 2011; American Society of Civil Engineers 2005)
Plant Machinery	Low	Water damage to electrical components	High	water damage to electrical components, debris strikes	High	water damage to electrical components, debris strikes, impact damage, washout	Low	(Horspool & Fraser 2015; Auckland Engineering Lifelines 2014; Bell et al. 2005; Graf et al. 2014; Kazama & Noda 2012; American Society of Civil Engineers 2005)
Planes	Negligible	Negligible	High	Small planes floated, debris strikes, impact damage	High	Planes floated, debris strikes, impact damage, fuel tanks breached	Low	(Horspool & Fraser 2015)
Energy								
Electricity								
Overhead Power Lines	Negligible	Negligible	Low-Medium	Lines severed from pulling of utility poles, shorting of inundated transformers	High	Debris strikes, lines severed, short circuiting, water damage, shorting of transformers, washout	Low	(Horspool & Fraser 2015; Edwards 2006; Evans & McGhie 2011; Kazama & Noda 2012; American Society of Civil Engineers 2005)
Buried Power Lines	Negligible - Low	Water infiltration of compromised cable housing	Low	Scour at building entry points, scour of backfill, exposure, water infiltration of compromised cable housing , ducting & cables across waterways or below bridges severed	Low-Medium	Scour at building entry points, scour of backfill, exposure, water infiltration of compromised cable housing , ducting & cables across waterways or below bridges severed, ducting & cables severed	Low	(Horspool & Fraser 2015; Auckland Engineering Lifelines 2014; Francis 2006)
Utility Poles	Negligible	Negligible	Low-Medium	Debris strikes, scour of foundations, shorting of inundated transformers	High	Debris strikes, scour and liquefaction of foundations, shorting of inundated transformers, tilting, shearing, washout	Medium - High	(Horspool & Fraser 2015; Francis 2006; Kazama & Noda 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Sub-stations	Negligible-Low	Shorting of low lying electrical components, silt coverage	Medium-High	Salt water contamination to electrical components & structures, debris and sediment cover, debris strikes, non-structural collapse to building, washout of some outdoor components	High	Salt water contamination to electrical components and structures, debris and sediment cover, debris strikes, non-structural collapse of building, washout	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Kazama & Noda 2012; Tang & Edwards 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)

Power Stations	Negligible	Negligible	Medium - High	Salt Water contamination to electrical components and structures, debris and sediment cover, non-structural collapse of building, washout of some outdoor components	High	Salt water contamination to electrical components and structures, debris and sediment cover, non-structural collapse, washout, shut down of cooling systems	Low	(Horspool & Fraser 2015; AON Benfield 2011; Kazama & Noda 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Petroleum								
Tanks	Negligible	Negligible	Negligible - Low	Debris strikes, buckling of tank base, lifting of empty or small tanks, scour of foundations	Medium-High	Sliding, overturning , debris strikes, scour & liquefaction of foundations, floating, impact damage, crushing, loss of fuel, fires	Low	(Horspool & Fraser 2015; Tomita et al. 2011; Ghobarah et al. 2006; AON Benfield 2011; McClelland 2011; Cruz et al. 2009; Francis 2006; Kim et al. 2014; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006)
Pipes	Negligible	Negligible	Low-Medium	Scour and exposure of buried pipes, utility bridges severed, pipes attached to mobilised tanks severed, debris strikes	Medium	Scour and exposure of buried pipes, utility bridges severed, pipes attached to mobilised tanks severed, debris strikes decoupling, fire	Low	(Horspool & Fraser 2015; AON Benfield 2011; Ghobarah et al. 2006; Cruz et al. 2009; Francis 2006)
Refinery Facilities	Low	Light debris and silt coverage shorting of low lying electrical components & plant machinery	High	Debris coverage, debris strikes, shorting of electrical components and plant machinery, oil spillage, non-structural collapse of buildings, washout of light structures, washout of outdoor components, fire, explosions	High	Debris coverage, debris strikes, shorting of electrical components and plant machinery, oil spillage, non-structural collapse of buildings, fire, explosions, washout	Medium	(Cruz et al. 2009; Graf et al. 2014; Tang & Edwards 2012; Reese et al. 2011)
Gas								
Storage	Low	Scour of foundations	Low-Medium	Lifting of empty and small tanks, debris strikes, scour to foundations	High	Scour of foundations, displacement of tanks, debris strikes, fires	Medium	(Horspool & Fraser 2015; Nojima 2012; Auckland Engineering Lifelines 2014; Francis 2006; Kazama & Noda 2012; Eguchi et al. 2013; Tang & Edwards 2012; Scawthorn et al. 2006)
Pipes	Low	Scour of backfill	Low	Scour of weak backfill, exposure, pipes crossing waterways and above ground severed by debris impacts,	Low-Medium	Bending and breakage, decoupling at entry point to buildings & floated tanks, scouring & exposure, fracturing, siltation, blockage, fire, wastage	Low	(Horspool & Fraser 2015; Nojima 2012; Francis 2006; Tang & Edwards 2012)
Water Wastewater & Sewerage								
Pumping Stations	Negligible – Low	Inundation of some electrical components	High	Contamination & failure of electrical & pumping equipment, sediment & debris cover, debris strikes	High	Contamination & failure of electrical & pumping equipment, sediment & debris cover, debris strikes, structural collapse, equipment washout	Medium	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Eguchi et al. 2013; Scawthorn et al. 2006; American Society of Civil Engineers 2005)

Pipes	Low	Silt infiltration	Low	Siltation, scour of weak backfill, exposure, bending, debris strikes, utility bridges severed by debris strikes	Medium	Scour, bending and breakage, decoupling & exposure, fracturing, siltation, blockage, utility bridges severed	Low	(Horspool & Fraser 2015; Villholth & Neupane 2011; Sagara & Ishiwatari 2012; Matsuhashi et al. 2012; Edwards 2006; Auckland Engineering Lifelines 2014; Ghobarah et al. 2006; Francis 2006; Lekkas 2011; Kim et al. 2014; Eguchi et al. 2013; Tang & Edwards 2012; American Society of Civil Engineers 2005)
Septic Tanks	Low	Salt water contamination	Low	Floating of exposed low volume polyurethane tanks, sedimentation, scour of weak backfill	Medium	Sediment infill, scour, floating of low volume tanks	Low	(Horspool & Fraser 2015; Villholth & Neupane 2011; Edwards 2006; Bell et al. 2005; Francis 2006; American Society of Civil Engineers 2005)
Treatment Facilities	Medium–High	Salt water contamination	High	Siltation, erosion of embankments, inundation of machinery, water damage of structure interiors, salt water contamination of filters pumps & ponds	High	Siltation, erosion of embankments, inundation of machinery, water damage of structure interiors, salt water contamination of filters pumps & ponds, washout	Medium	(Horspool & Fraser 2015; Villholth & Neupane 2011; Sagara & Ishiwatari 2012; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; Kazama & Noda 2012; Eguchi et al. 2013; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
<u>Drinking Water</u>								
Wells	Medium	Salt water contamination of shallow wells	High	Salt water & sewage contamination, groundwater contamination, debris strikes to components	High	Salt water & sewage contamination, ground water & aquifer contamination, scour, debris strikes, components exposed & washed away	Low	(Horspool & Fraser 2015; Villholth & Neupane 2011; Edwards 2006; Bell et al. 2005; Kim et al. 2014; Chandrasekar & Ramesh 2007; American Society of Civil Engineers 2005)
Pipes	Low	Minor siltation	Low	Scouring of weak backfill, exposure, debris strikes, utility bridges cracked or severed, non HDPE pipes severed, damage to water meters	Medium	Scouring and exposure, debris strikes, fracturing, siltation, blockages, severed, decoupling, severed, some HDPE pipes severed, damage to water meters	Low	(Horspool & Fraser 2015; Miyajima 2014; Villholth & Neupane 2011; Edwards 2006; Auckland Engineering Lifelines 2014; Ghobarah et al. 2006; Francis 2006; Kazama & Noda 2012; Lekkas 2011; Eguchi et al. 2013; Tang & Edwards 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Storage	Low	Salt water contamination	Low-Medium	Salt water and sewage contamination, siltation, debris strikes to tanks & reservoir embankments, low volume polyurethane tanks floated, scour of foundations, tilting of water towers	High	Salt water and sewage contamination, siltation, debris strikes to tanks & reservoir embankments, low volume polyurethane tanks floated, scour of foundations, tilting of water towers, floating of low volume concrete reservoirs, washout	Low	(Horspool & Fraser 2015; Villholth & Neupane 2011; Edwards 2006; Bell et al. 2005; Francis 2006; American Society of Civil Engineers 2005)
Treatment & Pump Facilities	Low	Water damage to electrical & mechanical equipment	Medium-High	Water damage to structure interiors, salt & sewage contamination, equipment & machinery washed away	High	Water damage to interiors, salt & sewage contamination, collapse of structures, equipment & machinery washed away	Low	(Villholth & Neupane 2011; Edwards 2006; Bell et al. 2005; Eguchi et al. 2013; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
<u>Stormwater</u>								
Outflow pipes	High	Sediment infiltration, scour	High	Scour, debris & sediment blockage	High	Scour, debris & sediment blockage, collapse of outflows, washout	Low	(Auckland Engineering Lifelines 2014)

Open drains and channels	Medium	Debris blockage	High	Scour of embankments, debris blockage, siltation, blocked culverts, removal of vegetation	High	Scour of embankments, debris blockage, siltation, blocked culverts, removal of vegetation, widening of unreinforced channels, covers lifted	Low	(Villholth & Neupane 2011; Edwards 2006; Auckland Engineering Lifelines 2014; Goff et al. 2006; Ghobarah et al. 2006; Francis 2006; Kazama & Noda 2012)
<u>Irrigation</u>								
Canals	Medium	Debris blockage, siltation, salt contamination	High	Scour of embankments, debris blockage, siltation, removal of vegetation, salt contamination	High	Scour of embankments, debris blockage, siltation, removal of vegetation, salt contamination	Low	(Kurian et al. 2007; American Society of Civil Engineers 2005)
Storage	Low	Salt contamination	Low-Medium	Salt contamination, scour of foundations, floating of low volume polyurethane tanks	High	Salt contamination, scour of foundations, floating of tanks, floating of low volume concrete reservoirs	Low	(Horspool & Fraser 2015; Villholth & Neupane 2011; Edwards 2006; Bell et al. 2005; Francis 2006; American Society of Civil Engineers 2005)
Machinery	Negligible - Low	Debris strikes	Medium	Debris strikes, water damage to electrical components, washout of outdoor equipment	High	Debris strikes, water damage to electrical components , washout	Low	(Horspool & Fraser 2015; Auckland Engineering Lifelines 2014; Bell et al. 2005; Graf et al. 2014; Kazama & Noda 2012; American Society of Civil Engineers 2005)
Pipes	Low	Minor siltation	Low	Scouring of weak backfill, exposure, debris strikes, utility bridges cracked or severed, decoupling	Medium	Scouring and exposure, debris strikes, fracturing, siltation, blockages, severed, decoupling	Low	(Horspool & Fraser 2015; Miyajima 2014; Villholth & Neupane 2011; Edwards 2006; Auckland Engineering Lifelines 2014; Ghobarah et al. 2006; Francis 2006; Kazama & Noda 2012; Lekkas 2011; Eguchi et al. 2013; Tang & Edwards 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Pumping Stations	Negligible – Low	Inundation of some electrical components	High	Contamination & failure of electrical and pumping equipment, sediment & debris cover, debris strikes	High	Contamination & failure of electrical and pumping equipment, sediment & debris cover, debris strikes, structural collapse, equipment washout	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Eguchi et al. 2013; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
<u>Flood Controls</u>								
Stop banks	Negligible	Negligible	Low	Removal of vegetation, scour	Medium	Scour, piping, removal of vegetation, blowouts, washout	Low	(Bell et al. 2005; Hart & Knight 2009; Chandrasekar & Ramesh 2007; Francis 2006)
Walls & Floodgates	Negligible	Negligible	Low	Scour of foundations, tilting of concrete blocks	Medium-High	Liquefaction and scour of foundations, tilting of concrete blocks, removal of materials - especially on backside & wall breaks	Low	(Suppasri, Mas & Imamura 2013; Edwards 2006; Bell et al. 2005; Cruz et al. 2009; Kazama & Noda 2012; Lekkas 2011; Kurian et al. 2007; Yeh et al. 2013; Saatcioglu 2007; American Society of Civil Engineers 2005; Francis 2006)
<u>Coastal Management</u>								
Sea walls	Negligible	Negligible	Low	Scour of foundations, tilting of concrete blocks	Medium-High	Liquefaction and scour of foundations, tilting of concrete blocks, removal of materials - especially on backside & wall breaks	Medium	(Suppasri, Mas & Imamura 2013; Edwards 2006; Bell et al. 2005; Cruz et al. 2009; Kazama & Noda 2012; Lekkas 2011; Kurian et al. 2007; Yeh et al. 2013; Saatcioglu 2007; American Society of Civil Engineers 2005)
Breakwaters	Negligible	Negligible	Negligible	Negligible	Low	Scour, removal of material, debris impact, sliding of caissons	Low	(Suppasri, Mas & Imamura 2013; Tomita et al. 2011; Francis 2006; Kazama & Noda 2012; Lekkas 2011; American Society of Civil Engineers 2005)
Dunes and Embankments	Negligible	Negligible	Low	Removal of vegetation, scour, debris coverage	Low – Medium	Loss of vegetation, scour, debris coverage, migration, washout	Low	(Bell et al. 2005; Hart & Knight 2009; Chandrasekar & Ramesh 2007)

Telecommunications Wireless								
Cellular Towers	Low	Erosion of base, tilting of supports	High	Erosion of base, titling, debris strikes, water damage of electrical components, buckling of monopole structures, washout of base station, washout	High	Erosion of base, titling, debris strikes, water damage of electrical components, collapse of tower, collapse of low rise supporting buildings, twisting of lattice type towers, washout of base stations, washout	Medium	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski & Tang 2012; Kwasinski 2013; Edwards 2006; Ghobarah et al. 2006; Lekkas 2011; Tang & Edwards 2012)
Exchange centres	High	Minor water damage to interiors & low lying generators	High	Scour of cables entering building, water damage to interior, shorting of electrical components & generators	High	Scour, damage to interiors, shorting of electrical components and generators, equipment washed away, collapse, washout	Medium	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski 2013; Edwards 2006; Francis 2006; Kazama & Noda 2012; Tang & Edwards 2012; Scawthorn et al. 2006)
Radio transmitters	Low	Erosion of tower base, tilting of supports	High	Erosion of tower base, titling, debris strikes, collapse of support towers	High	Erosion of base, titling, debris strikes, collapse of tower, collapse of low rise supporting buildings, washout	Low	(Horspool & Fraser 2015; Kwasinski 2013; Ghobarah et al. 2006; Scawthorn et al. 2006)
Internet								
Overhead Cables	Low	Scour of support base	High	Debris strikes to support, tilting of support pole, collapse of support, cables severed, water damage to components	High	Debris impacts to support, tilting of support pole, collapse of support, cables severed, water damage to components, collapse of support	Low	(Nagayama 2011; Horspool & Fraser 2015; McClelland 2011; Kazama & Noda 2012)
Buried cables	Low	Scour of weak backfill material, shorting of home switch boxes	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Low	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski & Tang 2012; Kwasinski 2013; Francis 2006)
Switch boxes	Medium	Water damage to internal components	High	Debris strikes, water damage to internal components, washout	High	Debris impacts, water damage to internal components, washout	Low	(Horspool & Fraser 2015; Kazama & Noda 2012)
Landline								
Overhead cables	Low	Scour of support base	High	Debris strikes to support, tilting of support pole, collapse of support, cables severed, water damage to components	High	Debris impacts to support, tilting of support pole, collapse of support, cables severed, water damage to components, collapse of supports	Low	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Kwasinski 2013; Kazama & Noda 2012; Scawthorn et al. 2006)
Buried cables	Low	Scour of backfill material	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Medium - High	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Low	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski & Tang 2012; Kwasinski 2013; Francis 2006)

Exchange centres	Medium	Minor water damage to interiors	High	Scour of foundations, water damage to interiors, short circuiting of electrical components, washout of light structures	High	Scour of foundations, water damage to interiors, short circuiting of electrical components, collapse, washout	Medium	(Nagayama 2011; Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Kwasinski 2013; Francis 2006; Kazama & Noda 2012; Tang & Edwards 2012; Scawthorn et al. 2006)
Switch boxes	Medium	Water damage to internal components	High	Debris strikes, water damage to internal components, washout	High	Debris impacts, water damage to internal components, washout	Low	(Horspool & Fraser 2015; Kazama & Noda 2012)

Appendix 7.4: Observed Tsunami impacts

Presented below are some key observations of tsunami impacts to infrastructure, made during a post-event field survey of damage following the 2015, 'Illapel' earthquake tsunami at Coquimbo, Chile:

Figure 7.6: Roads: Mostly performed well. Where significant damage occurred, it was often associated with a culvert running beneath that section of road.

Figure 7.7: Rail: Similar to roads, rail ballast seemed to experience the greatest damage where drainage flowed beneath. Also on stretches close to urban streets, sections of the lines were displaced more when corresponding with the termination of a street – i.e. there were likely higher flow speeds between blocks of buildings as water receded.

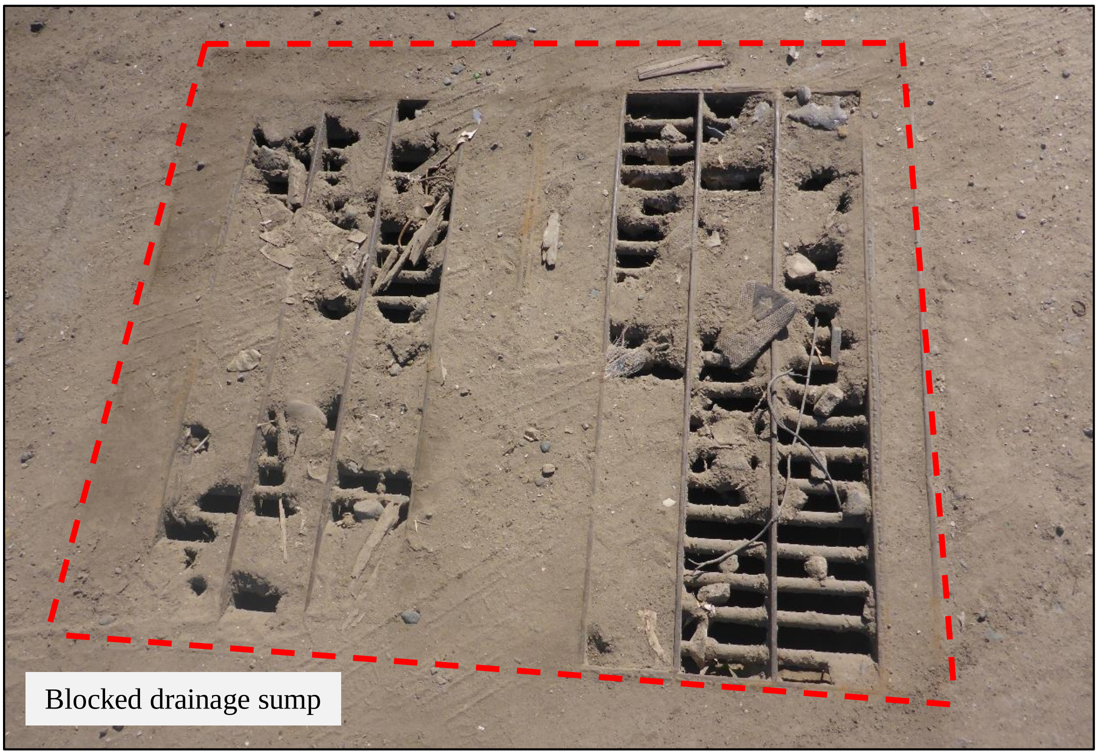

Figure 7.8: Stormwater: Drains were infilled with silt, sand and debris to various degrees at both high and low inundation depths

Figure 7.9: Stormwater: Steel culverts performed poorly and were associated with the most significant road washout. Concrete culverts mostly performed well but experienced significant scour on the seaward end (above).

Figure 7.10: LPG Tanks: Some tanks were pulled from bolts and floated inland.

Appendix 7.5: Level of Service Justifications

Infrastructure Type	Applicable Suburbs	Serviceable	Serviceability Decision Process
Wharves	*Lyttelton*	No	High probability of all but one wharf becoming damaged, medium probability wharf would only service small vessels. Larger vessels may still be able to dock along the front of the container yard if undamaged. Access would likely be restricted due to debris deposition, fluctuating water levels would make most wharves unsafe to dock at for up to 24 hours after final damaging wave has receded.
Rail	*Lyttelton*	No	Medium – High probability of damage in much of Lyttelton. Even if track is undamaged it is likely to be covered with debris, including shipping containers.
	Heathcote Valley	Yes	Rail is not inundated
Wireless Telecoms	*Sumner*	No	All cellular towers have a high probability of damage. North east orientation of the valley will likely restrict service from undamaged transmitters.
	Waimairi Beach, North Beach, Rawhiti, New Brighton, Aranui, Bexley, South Brighton, South Shore, Bromley, Ferrymead, Heathcote Valley, Mt Pleasant	Yes	Although most areas have a high probability of a cell tower being damaged, it is likely that the effective range of transmitter ranges outside of the inundation zone would overlap with the inundation zones in these suburbs.
	Moncks Bay, Lyttelton	Yes	Transmitters above each valley would likely provide coverage to the inundated area if they lose service from damaged towers.
Wastewater	*Sumner, Moncks Bay*	No	High probability of damage to pump stations and medium probability of damage to pipes across each suburb.
	New Brighton, Bexley	No	High probability of damage to pump station, low probability of damage to most pipes but some damage would be expected to network.
	South Brighton, South Shore	No	Both have to pass through the network associated with New Brighton and Bexley. Also a high probability of damage to one pump station and some damage would be expected to pipe network given a low probability of damage.
	Waimairi Beach, North Beach, Aranui, Rawhiti, Bromley, Ferrymead, Heathcote Valley, Lyttelton	Yes	Networks largely un-inundated and low probabilities of damage.

	Mt Pleasant	Yes	High probability of damage to pump station but gravity fed waste would likely be able to bypass into estuary. Outlet has a low probability of damage.
Stormwater	*Ferrymead*	Yes	Low probability of damage to pipes. High probability of damage to open drains however these would still likely drain water unless entirely infilled which is unlikely.
	Sumner, Moncks Bay	No	Medium Probability of damage to pipes across inundation area. Extensive damage to shore fronts likely where stormwater outlets are located
	Lyttleton, Waimairi Beach, North Beach, Mt Pleasant	Yes	Frequent low-medium probability of damage to pipes but not over extensive areas, outflows could be damaged but redundancies in network exist in most places.
	South Brighton, South Shore	No	Low-medium probability of damage for most of inundated area. Some areas may not be affected by loss of services due to proximity to estuary. Surface flooding on road would be expected.
Potable Water	*South Shore, South Brighton, New Brighton, Bexley*	No	Mostly low probabilities of damage but higher probabilities of building damage in these areas will likely result in privately owned pipe breakages resulting in loss of pressure for networks.
	Rawhiti, Waimairi Beach, North Beach, Aranui, Ferrymead, Heathcote Valley, Lyttelton	Yes	Networks largely un-inundated and pipes at low probability of damage.
	Mt Pleasant	Yes	Low probability of damage to pipes in inundation zone. Scour is likely along shore front which could affect damage and serviceability but is not considered in model. Appears to have redundancy built into network via Heathcote Valley
	Moncks Bay, Sumner	No	All of network dependant on the serviceability of two key bottlenecks both at medium probability of damage and also very susceptible to scour along shore front. Most pipes in inundation zones at medium probability of damage. Many buildings in these suburbs likely to be damaged resulting in privately owned pipes breaking and a loss of network water pressure.
Roads	*Waimairi Beach, North Beach, Aranui, Bexley, Ferrymead, Heathcote Valley, Lyttelton*	Yes	Networks mostly low probability of damage for roads and bridges. Not extensive inundation to network in these suburbs.
	Rawhiti, New Brighton, South Brighton	No	Despite low probabilities of damage these suburbs would likely have extensive debris deposition on road network. Despite modelling these suburbs are also more susceptible to scour than most given their proximity to coast.

	South Shore, Moncks Bay, Sumner	No	Low-Medium probabilities of damage would likely result in damage to bottlenecks especially due to scour along shore fronts. Extensive debris deposition would be expected in these suburbs from building damage.

Appendix 7.6: Christchurch City Suburbs

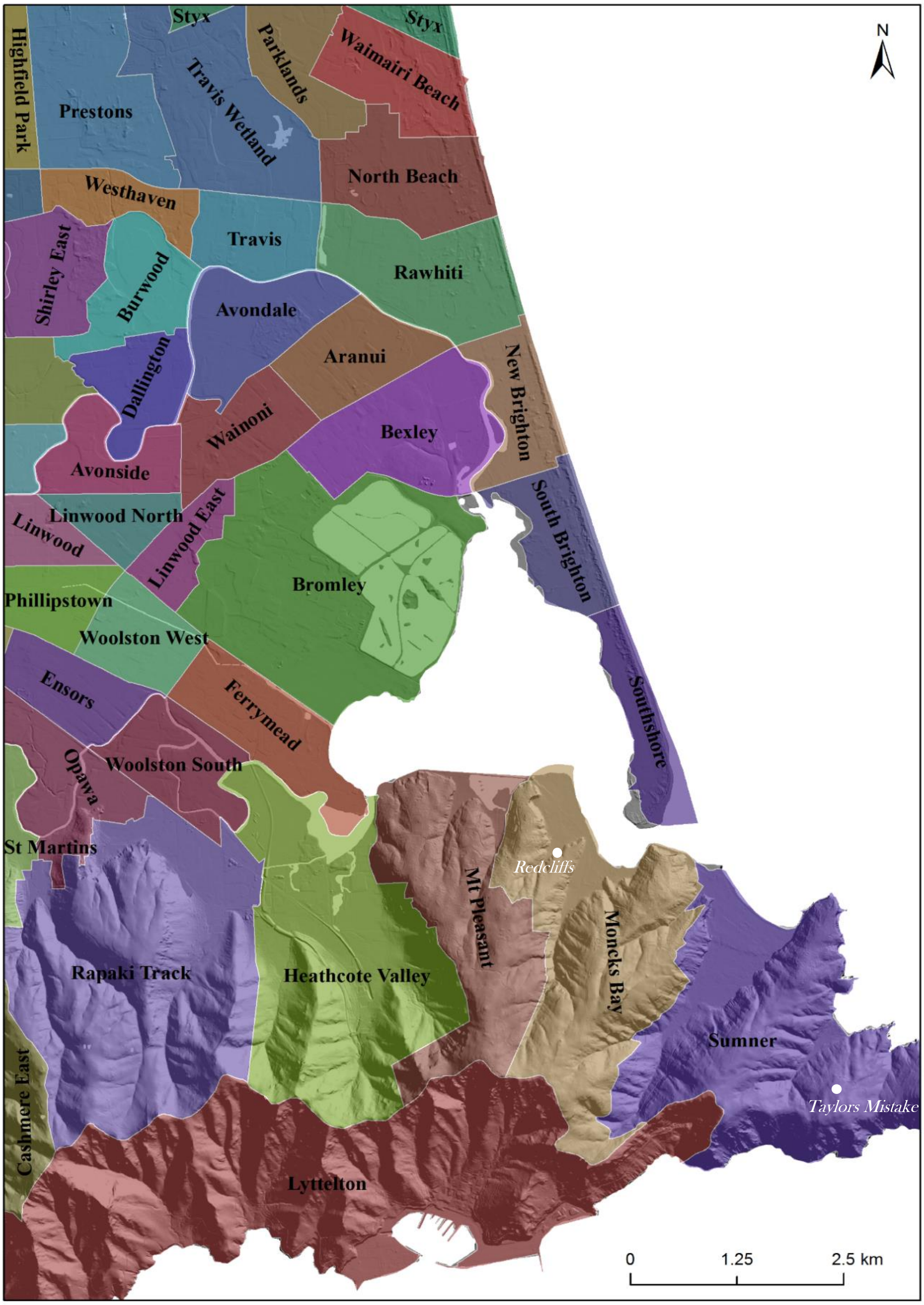

Figure 7.11: Map showing Christchurch city suburbs

Appendix 7.7: Response and Mitigation Options for Tsunami Impacts to Infrastructure

Infrastructural Asset	Damage Type	Response/Recovery options	Mitigation Options	Information quality	Sources
Transportation					
<u>*Roads*</u>					
Pavement	Sediment & debris cover	Clear by hand or with heavy machinery	Install water permeable fence alongside road to catch small-medium sized debris, develop rapid response plans to deploy heavy machinery, have multiple access routes to communities, elevate pavement	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Debris strikes	Reinstate severely damaged sections, fill small to medium holes with temporary backfill	Plant control forest, install reinforced barriers, Install water permeable fence alongside road to catch small-medium sized debris, elevate pavement	Medium	(Suppasri et al. 2013; PIANC Working Group 53 2009; Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005)
	Scour & liquefaction of base materials	Fill small to medium holes with temporary backfill, restrict traffic to four wheel drive access	Utilise multiple access routes to communities, use well compacted base material, install coastal protection	Medium	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009)
	Ponding	Pump excess water into drainage channels, restrict traffic to four wheel drive access, clear any blocked drainage channels by hand or with heavy machinery	Stockpile pumps outside of inundation zone, design and maintain good drainage systems, elevate pavement	Low	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Edwards 2006; Bell et al. 2005)
	Complete damage/washout	Replace washed out sections, divert traffic to undamaged routes, use temporary surfaces	Coastal protection, use well compacted base material, elevate pavement, develop rapid response plans to deploy repair workers and heavy machinery	High	(Akiyama et al. 2013; Ghobarah et al. 2006; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Suppasri et al. 2013; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
	Removal of signage & markings	Reinstate or replace damaged components, deploy traffic managers if required	Stockpile spare parts outside inundation zone, develop rapid response plans to deploy traffic managers	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
Bridges	Scour of embankments	Temporary backfill, reinstate	Utilise erosion protection, use U-shaped wing walls, longer wing wall	Medium	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
	Corrosion	Clean off salt, replace damaged components	Seal exposed metal, use cathodic protection, ensure regular structural surveys	Low	(Akiyama et al. 2013; Frangopol & Bocchini 2012; Kawashima & Buckle 2013)
	Channel widening	Replace material, rebuild embankments, construct longer superstructure and supports	Use erosion protection, vegetate embankments	Low	(Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
	Channel aggradation	Dredge channel, rebuild with elevated deck	Store dredging equipment outside of expected inundation zone, regular dredging of vulnerable channels,	Low	(Horspool & Fraser 2015; LRFD 2010; Edwards 2006; American Society of Civil Engineers 2005)
	Silt & debris cover	Clear by hand or with heavy machinery	Raise deck elevation, install reinforced barriers	Medium	(Horspool & Fraser 2015; Bell et al. 2005; Nakanishi et al. 2014; LRFD 2010; Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005)
	Debris strikes	Reinstate or replace damaged components	Use RC design, install bumpers on exposed sections, install reinforced barriers, elevate deck	High	(Horspool & Fraser 2015; Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; LRFD 2010)
	Scour of foundations	Replace backfill to non-damaged foundations	Use deep concrete foundations, install erosion protection around abutments	Medium	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; LRFD 2010; Bell et al. 2005)
	Damage to barriers	Install temporary barriers, reinstate or replace barriers	Reinforce barriers on both sides, install bumpers	High	(Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005; LRFD 2010)

		Complete damage/washout	Install temporary bridge, replace bridge, deploy ferry or barge services	Seismic strengthening of bridge, use monolithic connections, ensure continuity of superstructure, raise superstructure elevation, aerodynamic profile, install retainers, install vents in deck to alleviate buoyancy pressure, use RC design, elevate superstructure, install breakaway barriers to reduce debris build up and lateral forces, develop rapid response plans to deploy repair workers and heavy machinery, store ready-made temporary bridges and barges outside of expected inundation zone	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; Akiyama et al. 2013; Iemura et al. 2005; LRFD 2010; American Society of Civil Engineers 2005; Saatcioglu 2007; Tang & Edwards 2012; Kazama & Noda 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
		Removal of signage & markings	Reinstate or replace damaged components, deploy traffic managers if required	Stockpile spare parts outside inundation zone, develop rapid response plans to deploy traffic managers	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
	Lighting	Water damage to electrical components	Repair or replace damaged components	Develop rapid response plans to deploy repair workers, elevate electrical components on supports, stockpile spare parts outside of expected inundation zone, elevate on RC design supports	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Edwards 2006; Matsuhashi et al. 2012; Kwasinski 2013; Cruz et al. 2009)
		Debris strikes	Repair minor damages, replace structurally damaged supports	Use RC supports, attach to existing RC design utility poles, bury cables, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; McClelland 2011; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006)
		Foundation scour	Repair foundations, replace backfill if foundations undamaged	Use deep concrete foundations, use well compacted backfill material	Low	(Horspool & Fraser 2015; McClelland 2011; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Bell et al. 2005; Francis 2006; LRFD 2010)
		Complete damage/washout	Use temporary supports, deploy mobile generators, replace utility poles	Use RC supports, bury cables, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers, use deep concrete foundations, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; McClelland 2011; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Cruz et al. 2009; Francis 2006)
	Vehicles	Water damage to electrical components	Deploy public transport, reinstate damaged components, replace vehicle	Elevate parking, use water tight housing/seals on internal components, park outside of expected inundation zone if possible, develop rapid response plans to deploy public transport services	Low	(Nakanishi et al. 2014; American Society of Civil Engineers 2005; Cruz et al. 2009; Edwards 2006)
		Corrosion	Clean off salt, reinstate or replace damaged components, replace vehicle	Seal exposed metal, park outside of expected inundation zone if possible, elevate parking, install flood protection around parking	Low	(Bardal 2004)
		Debris strikes	Reinstate or replace damaged components, replace vehicle, deploy public transport	Elevate parking, fences/walls around parking, park outside of expected inundation zone if possible	Low	(Nakanishi et al. 2014; American Society of Civil Engineers 2005)
		Floating	Recover floated vehicles, reinstate or replace damaged components, replace vehicle, deploy public transport	Elevate parking, install fences/walls around parking, park outside of expected inundation zone if possible	Low	(Nakanishi et al. 2014; American Society of Civil Engineers 2005)
		Impact damage	Reinstate or replace damaged components, replace vehicle, deploy public transport	Elevate parking, install fences/walls around parking, park outside of expected inundation zone if possible, install bumpers	Low	(Nakanishi et al. 2014; American Society of Civil Engineers 2005)
<u>*Rail*</u>	*Tracks*	Silt & debris cover	Prioritise by route damage or importance, clear by hand or with heavy machinery	Install water permeable fence alongside track to catch small-medium sized debris, elevate track, develop rapid response plans to deploy heavy machinery	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Bell et al. 2005; Nakanishi et al. 2014; Unjoh 2012; McClelland 2011; Edwards 2006; Scawthorn et al. 2006)
		Ballast scour	replace ballast material and relay track	Use well compacted material, design and maintain adequate drainage systems, install coastal protection for coastal tracks, develop rapid response plans to deploy repair workers	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012)
		Complete damage/washout	Prioritise by route importance, relay ballast material, relay tracks	Stockpile spare parts outside inundation zone, develop rapid response plans to deploy repair workers, use coastal protection, plant control forests	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell & King 2009; Scawthorn et al. 2006)
		Removal of signage & markings	Reinstate or replace damaged components, deploy traffic managers if required	Stockpile spare parts outside inundation zone, develop rapid response plans to deploy traffic managers	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
	Bridges	Scour of embankments	Temporary backfill, reinstate	Utilise erosion protection, use U-shaped wing walls, longer wing wall	Medium	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
		Corrosion	Clean off salt, replace damaged components	Seal exposed metal, use cathodic protection, ensure regular structural surveys	Low	(Akiyama et al. 2013; Frangopol & Bocchini 2012; Kawashima & Buckle 2013)
		Channel widening	Replace material, rebuild embankments, construct longer superstructure and supports	Use erosion protection, vegetate embankments	Low	(Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
		Channel aggradation	Dredge channel, rebuild with elevated deck	Store dredging equipment outside of expected inundation zone, regular dredging of vulnerable channels,	Low	(Horspool & Fraser 2015; LRFD 2010; Edwards 2006; American Society of Civil Engineers 2005)

	Silt & debris cover	Clear by hand or with heavy machinery	Raise deck elevation, install reinforced barriers	Medium	(Horspool & Fraser 2015; Bell et al. 2005; Nakanishi et al. 2014; LRFD 2010; Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005)
	Debris strikes	Reinstate or replace damaged components	Use RC design, install bumpers on exposed sections, install reinforced barriers, elevate deck	High	(Horspool & Fraser 2015; Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; LRFD 2010)
	Scour of foundations	Replace backfill to non-damaged foundations	Use deep concrete foundations, install erosion protection around abutments	Medium	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; LRFD 2010; Bell et al. 2005)
	Damage to barriers	Install temporary barriers, reinstate or replace barriers	Reinforce barriers on both sides, install bumpers	High	(Edwards 2006; Iemura et al. 2005; American Society of Civil Engineers 2005; LRFD 2010)
	Complete damage/washout	Install temporary bridge, replace bridge, deploy ferry or barge services	Seismic strengthening of bridge, use monolithic connections, ensure continuity of superstructure, raise superstructure elevation, aerodynamic profile, install retainers, install vents in deck to alleviate buoyancy pressure, use RC design, elevate superstructure, install breakaway barriers to reduce debris build up and lateral forces, develop rapid response plans to deploy repair workers and heavy machinery, store ready-made temporary bridges and barges outside of expected inundation zone	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; Akiyama et al. 2013; Iemura et al. 2005; LRFD 2010; American Society of Civil Engineers 2005; Saatcioglu 2007; Tang & Edwards 2012; Kazama & Noda 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
Stations & Depots	Water damage to interiors	Reinstate or replace damaged components, wash out sediment & debris	Elevate foundations, install flood controls, elevate control rooms, set back from coast, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Wall collapse	Reinstate structure, rebuild walls if structure is structurally sound, use temporary facilities	Use multi-storey RC design, elevate foundations, set back from coast, use flood controls, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Debris strikes	Reinstate or replace damaged components if structurally undamaged	Install bumpers, elevate foundations, use RC design, install flood controls, set back from coast if possible, locate outside of expected inundation zone if possible, Install water permeable fences around facilities to catch small-medium sized debris	Low	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Water damage to electrical components & machinery	Reinstate or replace	Stockpile spare parts outside of inundation zone, make pre-disaster arrangements to move equipment to higher ground if possible, store equipment on high ground where possible, locate outside of inundation zone if possible	Low	(Edwards 2006; American Society of Civil Engineers 2005; Cruz et al. 2009)
	Complete damage/washout	Divert traffic to undamaged stations, use temporary facilities, rebuild facilities	Use multi-storey RC design, use breakaway walls on light structures, install coastal protection, install flood controls, elevate foundations, set back from coast, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
Overhead Lines	Scour of supports	Replace backfill if foundations undamaged, replace foundations	Use deep concrete foundations, use well compacted backfill	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Bell et al. 2005; Francis 2006; LRFD 2010)
	Water damage to electrical components	Replace damaged components	Elevate electrical components, stockpile spare parts outside of expected inundation zone, use water tight housing on transformers	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005; Matsuhashi et al. 2012; Kwasinski & Tang 2012; Kwasinski 2013)
	Debris strikes	Repair or replace damaged supports, replace damaged cables	Use RC supports, elevate track	Low	(Horspool & Fraser 2015; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Complete damage/washout	Replace supports and cables	Use RC supports, stockpile spare parts outside of expected inundation zone, make pre-disaster arrangements to deploy repair workers	Medium	(Horspool & Fraser 2015; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; PIANC Working Group 53 2009; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Scawthorn et al. 2006)
Trains	Derailment	Recover with heavy machinery	Park & locate yards outside of expected inundation zone if possible, develop rapid response plans to deploy heavy machinery	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Edwards 2006; Scawthorn et al. 2006; Cruz et al. 2009; American Society of Civil Engineers 2005)
	Debris strikes	Repair damaged components, replace vehicle	Stockpile spare parts outside of expected inundation zone, park outside of expected inundation zone if possible, elevate tracks	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Floating	Recover or dismantle with heavy machinery, replace vehicle	Park & locate yards outside of expected inundation zone if possible, develop rapid response plans to deploy heavy machinery, install reinforced barriers alongside tracks	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Edwards 2006; Scawthorn et al. 2006; Cruz et al. 2009; American Society of Civil Engineers 2005)
	Impact damage	Repair damaged components, replace vehicle	Stockpile spare parts outside of expected inundation zone, park outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Bell et al. 2005; Edwards 2006; Scawthorn et al. 2006; Cruz et al. 2009; American Society of Civil Engineers 2005)
Ports *Wharves & Piers*	Scour of foundations	Replace backfill to non-damaged foundations	Use deep concrete foundations, install erosion protection around abutments, regular underwater surveys of structure, install coastal protection	Medium	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; LRFD 2010; Bell et al. 2005)

	Debris strikes	Reinstate or replace damaged components	Install bumpers, make arrangements to anchor loose equipment & containers, make pre-disaster arrangements to move offshore (>50m water depth) if possible	High	(Horspool & Fraser 2015; Lynett et al. 2014; Iemura et al. 2005; LRFD 2010; Auckland Engineering Lifelines 2014; Cruz et al. 2009; Fritz et al. 2011; Scawthorn et al. 2006; PIANC Working Group 53 2009) Eskijan 2012
	Sediment & debris cover	Clear by hand or with heavy machinery	Install permeated fences, develop rapid response plans to deploy heavy machinery, build in redundancies, elevate pavement	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Aggradation of seabed	Dredge seabed, elevate wharves and piers	Store dredging machinery outside of expected inundation zone, dredge vulnerable areas regularly, design facilities to allow for aggradation	Low	(Horspool & Fraser 2015)
	Debris in waterways	Salvage large debris	Develop rapid response plans to deploy salvage crews, store salvaging equipment outside of expected inundation zone	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012)
	Removal of deck	Repair or replace sections	Design to withstand tsunami forces, install vents to reduce buoyancy pressure, seismic retrofitting, install coastal protection	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; LRFD 2010; PIANC Working Group 53 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Cruz et al. 2009)
	Complete damage/washout	Reroute vessels to undamaged ports, rebuild	Design to withstand tsunami forces, make pre-disaster arrangements to deploy repair workers, install coastal protection, regular underwater surveys of structure, seismic retrofitting	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; LRFD 2010; PIANC Working Group 53 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Cruz et al. 2009; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006)
Buildings	Water damage to interiors & stored goods	Reinstate or replace damaged components, wash out sediment & debris, inspect impacted stored goods and repack or dispose	Elevate foundations, install flood controls, elevate storage platforms, set back from coast, locate on high ground if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Complete damage/washout	Erect temporary facilities & storage buildings, transport goods to inland storage facilities, rebuild	Use multi-storey RC design, use breakaway walls on light structures, install coastal protection, install flood controls, elevate foundations, set back from coast, locate on high ground if possible	High	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
Plant Machinery	Water damage to electrical components & machinery	Reinstate or replace	Stockpile spare parts outside of expected inundation zone, make pre-disaster arrangements to move equipment to higher ground if possible, store equipment on high ground where possible	Low	(Edwards 2006; American Society of Civil Engineers 2005)
	Complete damage/washout	Recover equipment, replace equipment	Make pre-disaster arrangements to secure or elevate machinery if possible, store in RC design buildings, store equipment on high ground where possible	Low	(Horspool & Fraser 2015)
Vessels	Floated inland	Recover with heavy machinery or dismantle	Make pre-disaster arrangements to move vessels offshore (>50m water depth) if possible, plant control forests	High	(Lynett et al. 2014; Horspool & Fraser 2015; Suppasri et al. 2013; Auckland Engineering Lifelines 2014; Cruz et al. 2009; Scawthorn et al. 2006; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Fritz et al. 2011)
	Impact Damage/Debris Strikes	Reinstate or replace damaged components, replace vessel	Make pre-disaster arrangements to move vessels offshore (>50m water depth) if possible, install bumpers, reinforce hulls	Low	(Lynett et al. 2014; Horspool & Fraser 2015; Auckland Engineering Lifelines 2014; Cruz et al. 2009; Fritz et al. 2011; Scawthorn et al. 2006; PIANC Working Group 53 2009; American Society of Civil Engineers 2005)
Containers	Floated	Recover with heavy machinery	Secure container stacks when stored, make pre- disaster arrangements to lash container stacks if possible	Medium	(Horspool & Fraser 2015; Auckland Engineering Lifelines 2014)
	Debris & impact damage	Replace if necessary	Secure container stacks when stored, make pre-disaster arrangements to secure containers if possible, install coastal protection	Low	Horspool & Fraser 2015; Auckland Engineering Lifelines 2014
	Damage to goods	Inspect goods, repack or dispose of	Secure goods inside container, pack appropriately, secure container stacks when stored, make pre-disaster arrangements to secure container stacks, use water tight container seals, install flood controls	Medium	Horspool & Fraser 2015; Auckland Engineering Lifelines 2014
<u>*Airports*</u> *Runway*	Ponding	Pump excess water into drainage channels, clear any blockages in drainage channel by hand or heavy machinery	Stockpile pumps outside of expected inundation zone, design and maintain good drainage systems, elevate pavement, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Edwards 2006; Bell et al. 2005; Cruz et al. 2009)
	Sediment & debris cover	Clear by hand or with heavy machinery	Install permeated fence alongside runway, develop rapid response plans to deploy heavy machinery, install flood controls, locate outside of expected inundation zone if possible	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009; Cruz et al. 2009)
	Damage to lighting	Replace damaged components	Stockpile spare parts outside of expected inundation zone, elevate, reinforce supports	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)

Buildings	Water damage to interiors & stored goods	Reinstate or replace damaged components, wash out sediment & debris, inspect goods & repack or dispose	Elevate foundations, install flood controls, elevate storage platforms, set back from coast, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Complete damage/washout	Erect temporary facilities & storage buildings, transport goods to inland storage facilities, rebuild	Use multi-storey RC design, use breakaway walls on light structures, install coastal protection, install flood controls, elevate foundations, set back from coast, locate on high ground if possible	High	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
Plant Machinery	Water damage to electrical components & machinery	Reinstate or replace	Stockpile spare parts outside of inundation zone, make pre-disaster arrangements to move equipment to higher ground if possible, store equipment on high ground if possible, locate outside of expected inundation zone if possible	Low	(Edwards 2006; American Society of Civil Engineers 2005)
	Complete damage/washout	Recover equipment, replace equipment	Make pre-disaster arrangements to secure or elevate machinery if possible, store in RC design buildings, store equipment on high ground where possible, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
Planes	Debris strikes	Reinstate or replace damaged components, replace plane	Stockpile spare parts outside of inundation zone, make pre-disaster plans to divert all air traffic to airports outside of expected inundation zone if possible	Low	(Edwards 2006; American Society of Civil Engineers 2005)
	Impact damage	Reinstate or replace damaged components, replace plane	Make pre-disaster plans to divert all air traffic and grounded planes to airports outside of expected inundation zone if possible, make pre-disaster plans to secure or take off if possible	Low	(American Society of Civil Engineers 2005)
	Floating	Recover or dismantle with heavy machinery	Make pre-disaster plans to divert all air traffic and grounded planes to airports outside of expected inundation zone if possible, make pre-disaster plans to secure or take off if possible	Low	(American Society of Civil Engineers 2005)
Energy <u>*Electricity*</u> *Overhead Power Lines*	Shorting of transformers	Repair or replace damaged components, deploy mobile generators	Make pre-disaster arrangements to deploy repair workers, elevate transformers on supports, water tight housing for transformers, bury cables, stockpile spare parts & generators outside of expected inundation zone	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Edwards 2006; Matsuhashi et al. 2012; Kwasinski 2013; Cruz et al. 2009)
	Debris strikes	Replace damaged lines, deploy mobile generators	Make pre-disaster arrangements to deploy repair workers, bury cables, stockpile spare parts & generators outside of expected inundation zone, set back from coast if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Edwards 2006; Matsuhashi et al. 2012; Kwasinski 2013)
	Complete damage/washout	Use temporary supports, replace lines, deploy mobile generators	Make pre-disaster arrangements to deploy repair workers, bury cables, stockpile spare parts & generators outside of expected inundation zone, set back from coast if possible	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Edwards 2006; Matsuhashi et al. 2012; Kwasinski 2013)
Utility Poles	Debris strikes	Repair minor damages, use temporary supports, replace structurally damaged poles	Use RC supports, bury cables, stockpile spare parts outside of expected inundation zone, make pre-disaster arrangements to deploy repair workers	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; McClelland 2011; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006)
	Foundation scour	Repair foundations, replace backfill if foundations undamaged	Bury cables, use deep concrete foundations, use well compacted backfill material	Medium	(Horspool & Fraser 2015; McClelland 2011; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Bell et al. 2005; Francis 2006; LRFD 2010)
	Complete damage/washout	Use temporary supports, deploy mobile generators, replace utility poles	Use RC supports, bury cables, stockpile spare parts outside of expected inundation zone, make pre-disaster arrangements to deploy repair workers, use deep concrete foundations, locate outside of expected inundation zone if possible	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski 2013; Edwards 2006; Evans & McGhie 2011; American Society of Civil Engineers 2005; McClelland 2011; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006; Cruz et al. 2009; Francis 2006)
Buried Power Lines	Water infiltration of compromised cable housing	Replace damaged cables, deploy mobile generators	Make arrangements to deploy repair workers, stockpile spare parts & mobile generators outside of expected inundation zone	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Unjoh 2012; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006)
	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Cables & ducting over waterways severed	Lay temporary supports and new cable, attach to existing or temporary bridges, rebuild utility bridge	Develop response plans to deploy repair workers, bury beneath waterway if possible, attach to RC bridge, install protection buffers	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
Sub-stations	Shorting of electrical components	Replace damaged components, deploy mobile substation and generator	Install flood controls, elevate equipment and electrical components, locate outside of expected inundation zone if possible, develop rapid response plans to deploy repair workers	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Matsuhashi et al. 2012; Kwasinski 2013; Edwards 2006)

	Silt & debris cover	Clear by hand or with heavy machinery, deploy mobile substation and generator	locate outside of expected inundation zone if possible, make pre-disaster arrangements to deploy heavy machinery, install water permeable fences around facilities to catch small-to-medium sized debris	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Bell et al. 2005; Nakanishi et al. 2014; Edwards 2006; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or replace damaged equipment & facilities, deploy mobile substation and generator	locate outside of expected inundation zone if possible, install water permeable fences around facilities to catch small-to-medium sized debris, house equipment inside RC design buildings	Low	(Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Kwasinski 2013; Cruz et al. 2009)
	Complete damage/washout	Deploy mobile substations and generators, rebuild	Install flood controls, locate outside of expected inundation zone, use RC design buildings, install water tight doors, stockpile mobile sub-stations and generators outside of expected inundation zone, house all facilities in RC buildings	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
Power Stations	Water damage to interiors	Reinstate or replace damaged components, wash out sediment & debris	Elevate foundations, install flood controls, elevate control rooms, set back from coast, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Water damage and shorting of electrical components	Replace damaged components, deploy mobile generator	Install flood controls, elevate equipment and electrical components, locate outside of expected inundation zone if possible, develop rapid response plans to deploy repair workers	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Silt & debris cover	Clear by hand or with heavy machinery, deploy mobile generator	locate outside of expected inundation zone if possible, make pre-disaster arrangements to deploy heavy machinery, install water permeable fences around facilities to catch small-to-medium sized debris	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Bell et al. 2005; Nakanishi et al. 2014; Edwards 2006; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or replace damaged equipment & facilities, deploy mobile generator	locate outside of expected inundation zone if possible, install water permeable fences around facilities to catch small-to-medium sized debris, house equipment inside RC design buildings	Low	(Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Kwasinski 2013; Cruz et al. 2009)
	Shut down of cooling systems	Deploy repair workers if possible, shut down facilities	Install flood controls, locate outside of expected inundation zone if possible, develop emergency shutdown procedures, make pre-disaster arrangements to deploy repair workers, install coastal protection	Low	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005; Hart & Knight 2009)
	Complete damage/washout	Deploy mobile generators, rebuild	Install flood controls, locate outside of expected inundation zone, use RC design buildings, install water tight doors, stockpile mobile sub-stations and generators outside of expected inundation zone, house all facilities in RC design buildings, plant control forests, diversify electricity generation	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
<u>Petroleum</u> *Tanks*	Debris strikes	Repair or replace damaged components, replace tank	install water permeable fences around 'tank farms' to catch small-to-medium sized debris, secure loose objects and equipment if possible, install flood controls, elevate foundations, place on high ground if possible, use artificial high ground if possible, set back from coast if possible	Low	(Horspool & Fraser 2015; PIANC Working Group 53 2009; Edwards 2006; Cruz et al. 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Auckland Engineering Lifelines 2014)
	Scour of foundations	Replace backfill of undamaged foundations	Use deep concrete foundations, use well compacted backfill, install erosion protection around foundations	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005)
	Loss of fuel	Deploy oil containment and collection workers	Utilise spillage control walls, store recovery equipment outside of expected inundation zone, develop rapid response plans to deploy containment workers, locate on high ground, set back from coast if possible	Medium	(Cruz et al. 2009; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Suppasri et al. 2013; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009)
	Fire/explosions	Deploy firefighting crews, replace damaged tanks	Develop rapid response plans to deploy firefighting crews, make pre-disaster arrangements to remove fuel if possible	Low	(Cruz et al. 2009)
	Floating & washout	Recover or dismantle tanks	Use larger capacity storage tanks, make arrangements to fill low volume tanks with liquids if possible, anchor to foundations, elevate foundations, locate on higher ground if possible, construct artificial high ground, retrofit to seismic standards, plant control forests, install coastal protection	Medium	(Horspool & Fraser 2015; Cruz et al. 2009; Scawthorn et al. 2006; PIANC Working Group 53 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)
Pipes	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Washout of pipes over waterway	Lay temporary supports and new pipe, attach new or temporary pipes to existing or temporary bridges, rebuild utility bridge	Burry beneath waterway if possible, elevate utility bridges, attach to RC bridge, install protection buffers, stockpile spare parts outside of inundation zone, develop rapid response plans to deploy repair workers	Medium	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
	Decoupling	Reinstate, install temporary linkages, replace connectors	Stockpile spare parts outside of inundation zone, develop response plans to deploy repair workers, bury pipes	Low	(Horspool & Fraser 2015; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Edwards 2006)

Refinery Facilities	Debris and silt cover	Clear by hand or with heavy machinery, deploy mobile generator	locate outside of expected inundation zone if possible, make pre-disaster arrangements to deploy heavy machinery, install water permeable fences around facilities to catch small-to-medium sized debris	High	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Bell et al. 2005; Nakanishi et al. 2014; Edwards 2006; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or replace damaged equipment & facilities, deploy mobile generator	locate outside of expected inundation zone if possible, secure loose objects & containers, install water permeable fences around facilities to catch small-to-medium sized debris, house equipment inside RC design buildings	Low	(Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Kwasinski 2013; Cruz et al. 2009; Auckland Engineering Lifelines 2014)
	Water damage and shorting of electrical components	Replace damaged components, deploy mobile generator	Install flood controls, elevate equipment and electrical components, locate outside of expected inundation zone if possible, develop rapid response plans to deploy repair workers	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Loss of fuel	Deploy oil containment & collection crews	Utilise spillage control walls, store recovery equipment outside of expected inundation zone, develop rapid response plans to deploy containment workers, locate on high ground, set back from coast if possible	Medium	(Cruz et al. 2009; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Suppasri et al. 2013; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009)
	Fire/explosions	Deploy firefighting crews, replace damaged tanks	Develop rapid response plans to deploy firefighting crews, make pre-disaster arrangements to remove fuel and dangerous goods if possible	Low	(Cruz et al. 2009)
	Complete damage/washout	Erect temporary facilities & storage buildings, transport goods to inland storage facilities, rebuild	Use multi-storey RC design, use breakaway walls on light structures, install coastal protection, install flood controls, elevate foundations, set back from coast, locate on high ground if possible	High	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
<u>Gas</u> *Storage*	Scour of foundations	Replace backfill of undamaged foundations	Use deep concrete foundations, use well compacted backfill, install erosion protection around foundations	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005)
	Debris strikes	Repair or replace damaged components, replace tank	install water permeable fences around tanks to catch small-to-medium sized debris, secure loose objects and equipment if possible, install flood controls, elevate foundations, place on high ground if possible, use artificial high ground if possible, set back from coast if possible	Low	(Horspool & Fraser 2015; PIANC Working Group 53 2009; Edwards 2006; Cruz et al. 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Auckland Engineering Lifelines 2014)
	Floating & washout	Recover or dismantle tanks with heavy machinery	Use larger capacity storage tanks, make arrangements to fill low volume tanks with liquids if possible, anchor to foundations, elevate foundations, locate on higher ground if possible, construct artificial high ground, retrofit to seismic standards, plant control forests, install coastal protection	Medium	(Horspool & Fraser 2015; Cruz et al. 2009; Scawthorn et al. 2006; PIANC Working Group 53 2009; Suppasri et al. 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)
	Fire/explosions	Deploy firefighting crews, replace damaged tanks	Make rapid response plans to deploy firefighting crews, make pre-disaster arrangements to remove fuel if possible	Low	(Cruz et al. 2009)
Pipes	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Washout of pipes over waterway	Lay temporary supports and new pipe, attach new or temporary pipes to existing or temporary bridges, rebuild utility bridge	Burry beneath waterway if possible, elevate utility bridges, attach to RC bridge, install protection buffers, stockpile spare parts outside of inundation zone, develop rapid response plans to deploy repair workers	Medium	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
	Decoupling	Reinstate, install temporary linkages, replace connectors	Stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers, bury pipes	Low	(Horspool & Fraser 2015; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Edwards 2006)
Water <u>Wastewater & Sewerage</u> *Pipes*	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Decoupling	Reinstate, install temporary linkages, replace connectors	Use HDPE pipes, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers and water trucks	Low	(Horspool & Fraser 2015; Miyajima 2014; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Matsuhashi et al. 2012; Edwards 2006)
	Washout of pipes over waterway	Lay temporary supports and new pipe, attach new or temporary pipes to existing or temporary bridges, rebuild utility bridge	Burry beneath waterway if possible, elevate utility bridges, attach to RC bridge, protection buffers, use HDPE pipe, stockpile spare parts outside of inundation zone, develop rapid response plans to deploy repair workers	Medium	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
	Complete damage/washout	Lay temporary HDPE pipes, replace pipes,	Stockpile spare parts outside of expected inundation zone, use HDPE pipes, develop rapid response plans to deploy repair workers, use erosion protection	Medium	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Scawthorn et al. 2006; Francis 2006)

Pumping Stations	Salt water contamination	Shut off intakes, reinstate or replace, flush out wastewater intakes	Seal openings, make pre-disaster arrangements to shut off intake facilities, locate outside of expected inundation zone if possible, make pre-disaster arrangements to cover outlets if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Sediment & debris cover	Clear by hand or with heavy machinery	Install water permeable fences around pumping station to catch small-to-medium sized debris, use water tight housing, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or replace damaged components	Install water permeable fences, elevate facilities, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Water damage to electrical components	Replace damaged components	Stockpile spare parts outside of expected inundation zone if possible, use water tight housing for electronic panels, elevate electrical components, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009; Cruz et al. 2009; American Society of Civil Engineers 2005)
	Complete damage/washout	Deploy temporary pumps, reinstate, replace	Stockpile spare pumps outside of expected inundation zone, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005)
Septic Tanks	Salt water contamination	Pump out contents	Seal openings, elevate vents	Low	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Villholth & Neupane 2011)
	Floating	Recover or dismantle with heavy machinery	Make pre-disaster arrangements to fill low volume tanks with liquid if possible, use concrete tanks	Medium	(Bell et al. 2005; Scawthorn et al. 2006; PIANC Working Group 53 2009)
	Scour of backfill	Replace backfill if tank undamaged	Use well compacted materials, bury at adequate depth	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005)
	Sediment infiltration	Pump out contents, flush out tank	Seal openings, elevate vents	Low	(American Society of Civil Engineers 2005; Villholth & Neupane 2011)
Treatment Facilities	Salt water contamination of filters, pumps & ponds	Shut off intakes & pumps, replace damaged components, pump out contaminated sewage, deploy temporary bioreactors	Stock portable facilities (bioreactors) outside of expected inundation zone, seal openings, make pre-disaster arrangements to shut off intake facilities, make pre-disaster arrangements to cover outlets if possible, make pre-disaster arrangements to place concrete covers over reaction tanks if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Scawthorn et al. 2006)
	Silt & debris cover	Clear by hand or with heavy machinery	Make rapid response plans to deploy heavy machinery, install water permeable fences around facilities to catch small-to-medium sized debris, elevate facilities if possible, set back from coast if possible, locate outside of expected inundation zone if possible	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Scour of embankments	Temporary fill, repair damaged sections, replace material	Elevate embankments, use coastal protection, use erosion protection, vegetate embankments	Low	(Horspool & Fraser 2015; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Francis 2006)
	Water damage to electrical components & plant machinery	Replace damaged components, reinstate or replace machinery	Stockpile spare parts outside of expected inundation zone, use water tight housing for electronic panels, install water tight doors, elevate electrical components	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Cruz et al. 2009; Kwasinski 2013; Kwasinski & Tang 2012; Matsuhashi et al. 2012)
	Water damage to interiors	Reinstate or replace damaged components, wash out sediment & debris	Elevate foundations, install flood controls, elevate control rooms, set back from coast if possible, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Complete damage/washout	Divert intakes to operable facilities if possible, bypass treatment facilities, use temporary facilities, rebuild, deploy temporary bioreactors	Stock portable facilities (bioreactor) outside of expected inundation zone, locate outside of expected inundation zone if possible, use RC buildings	Medium	(Horspool & Fraser 2015; Suppasri et al. 2013; Sagara & Ishiwatari 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Edwards 2006; Cruz et al. 2009)
<u>*Drinking Water*</u> *Pipes*	Decoupling	Reinstate, install temporary linkages, replace connectors, deploy mobile water trucks and tanks	Use HDPE pipes, stockpile spare parts, tanks & water trucks outside of expected inundation zone, develop rapid response plans to deploy repair workers and water trucks	Low	(Horspool & Fraser 2015; Miyajima 2014; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Matsuhashi et al. 2012; Edwards 2006)
	Washout of pipes over waterway	Lay temporary supports and new pipe, attach new or temporary pipes to existing or temporary bridges, rebuild utility bridge, deploy mobile water trucks & tanks	Burry beneath waterway if possible, elevate utility bridges, attach to RC bridge, install protection buffers, use HDPE pipe, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers & water trucks	Medium	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible, use erosion protection	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Francis 2006)
	Complete damage/washout	Lay temporary HDPE pipes, replace pipes, deploy water trucks & tanks	Stockpile spare parts outside of expected inundation zone, use HDPE pipes, develop rapid response plans to deploy repair workers & water trucks, use erosion protection	Medium	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Scawthorn et al. 2006; Francis 2006)

Wells	Salt & sewage contamination	Pump out salt water, abandon well, deploy water trucks & bottled water	Stockpile water outside of inundation zone, make arrangements to use unaffected facilities, raise standpipes, locate outside of expected inundation zones if possible, seal grated well lids, reinforce well heads, develop rapid response plans to deploy repair workers & water trucks	Medium	(Miyajima 2014; Horspool & Fraser 2015; Villholth & Neupane 2011; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Edwards 2006)
	Damage to well components	Repair or replace damaged components, deploy water trucks & bottled water	Use protective housing, reinforce well heads, elevate standpipe, develop rapid response plans to deploy repair workers & water trucks	Medium	(Miyajima 2014; Horspool & Fraser 2015; Villholth & Neupane 2011; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005)
Storage	Salt water contamination	Pump out contents	Seal openings, elevate vents	Low	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Villholth & Neupane 2011)
	Debris strikes & Impact damage	Reinstate or replace damaged components	install water permeable fences around storage tanks to catch small-to-medium sized debris, elevate tank, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Floating of tanks & concrete reservoirs	Recover or dismantle with heavy machinery, deploy water trucks & bottled water	Make pre-disaster arrangements to fill low volume tanks with liquid if possible, use concrete tanks, elevate tanks on multi-storey RC building or elevated steel supports	Medium	(Bell et al. 2005; Scawthorn et al. 2006; PIANC Working Group 53 2009)
	Scour of foundations	Replace backfill of undamaged foundations	Use deep concrete foundations, use well compacted backfill, install erosion protection around foundations	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005)
	Tilting or collapse of water tower	Repair or replace, deploy mobile water trucks & bottled water	Anchor to supports, use deep concrete foundations, locate outside of expected inundation zone if possible, use monopole structure	Low	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Scawthorn et al. 2006)
Treatment & Pump Facilities	Water damage to interiors	Reinstate or replace damaged components, wash out sediment & debris	Elevate foundations, install flood controls, elevate control rooms, set back from coast if possible, locate on high ground if possible, locate outside of expected inundation zone if possible	Medium	(Mas et al. 2012; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Water damage to electrical components	Replace damaged components	Stockpile spare parts outside of expected inundation zone, use water tight housing for electronic panels, elevate electrical components, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009; Cruz et al. 2009; American Society of Civil Engineers 2005)
	Salt water contamination	Shut off intakes, reinstate or replace, flush out water intakes	Seal openings, make pre-disaster arrangements to shut off intake facilities, locate outside of expected inundation zone if possible, make pre-disaster arrangements to cover intakes and outlets if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Complete damage/washout	Divert intakes to operable facilities if possible, use temporary facilities, rebuild, deploy water trucks & bottled water	Use multi-storey RC design, use breakaway walls on light structures, install coastal protection, install flood controls, elevate foundations, set back from coast, locate on high ground if possible, make pre-disaster arrangements to deploy water trucks & bottled water	Medium	(Horspool & Fraser 2015; Suppasri et al. 2013; Sagara & Ishiwatari 2012; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Edwards 2006; Cruz et al. 2009)
<u>*Stormwater*</u> *Outflows*	Sediment and debris blockage	Clear debris by hand or with heavy machinery	Install grates on openings, make pre-disaster arrangements to cover outlets if possible	Low	(Horspool & Fraser 2015; King & Bell 2006; Nakanishi et al. 2014)
	Scour of outlet	Replace material if undamaged	Use well compacted material if possible, use deep concrete foundations, use erosion protection around outflow	Low	(Horspool & Fraser 2015; Edwards 2006)
	Complete damage/washout	Reinstate or replace, deploy repair workers	Install coastal protection, extend offshore, use erosion protection around outflows, make pre-disaster arrangements to deploy repair workers	Low	(Horspool & Fraser 2015; Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Francis 2006; American Society of Civil Engineers 2005)
Open Drains & Channels	Sediment and debris blockage	Deploy pumps in areas vulnerable to ponding, dig temporary drainage channels with heavy machinery, clear debris by hand or with heavy machinery	Install grates on intakes, install covers on open channels, use buried pipes, develop rapid response plans to deploy heavy machinery, install water permeable fence alongside channel to catch small-to-medium sized debris	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; King & Bell 2006; Nakanishi et al. 2014; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; Unjoh 2012; McClelland 2011; Scawthorn et al. 2006; PIANC Working Group 53 2009)
	Covers lifted	Replace covers	Anchor covers, use buried pipes	Low	(Horspool & Fraser 2015; Kwasinski 2013; McClelland 2011)
	Scour & widening of channels	Reinstate embankments	Use erosion protection on embankments, vegetate embankments, reinforce channel, cover channel, lay buried pipes	Low	(Horspool & Fraser 2015; Kwasinski 2013; McClelland 2011; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
<u>*Irrigation*</u> *Canals*	Sediment and debris blockage	Deploy pumps in areas vulnerable to ponding, clear debris by hand or with heavy machinery	Install grates on intakes, install covers to open channels if possible, use buried pipes, develop rapid response plans to deploy heavy machinery, install water permeable fence alongside canal to catch small-to-medium sized debris	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; King & Bell 2006; Nakanishi et al. 2014; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; Unjoh 2012; McClelland 2011; Scawthorn et al. 2006; PIANC Working Group 53 2009)
	Salt water contamination	Shut off intakes, abandon canal until contamination has been washed out, use alternative water supply	Elevate embankments, use flood controls, make pre-disaster arrangements to use alternative water supply	Same as flood control	(Villholth & Neupane 2011)control

Storage	Scour of embankments	Reinstate embankments	Use erosion protection on embankments, vegetate embankments, reinforce channel, lay buried pipes	Low	(Horspool & Fraser 2015; Kwasinski 2013; McClelland 2011; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005)
	Salt water contamination	Pump out contents	Seal openings, elevate vents	Low	(Horspool & Fraser 2015; American Society of Civil Engineers 2005; Villholth & Neupane 2011)
	Scour of foundations	Replace backfill of undamaged foundations	Use deep concrete foundations, use well compacted backfill, install erosion protection around foundations	Low	(Horspool & Fraser 2015; Edwards 2006; Bell et al. 2005; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005)
	Floating of tanks & concrete reservoirs	Recover or dismantle with heavy machinery, use alternative water supply	Make pre-disaster arrangements to fill low volume tanks with liquid if possible, use concrete tanks, elevate tanks, make pre-disaster arrangements to use alternative water supply	Medium	(Bell et al. 2005; Scawthorn et al. 2006; PIANC Working Group 53 2009)
	Debris strikes & impact damage	Reinstate or replace damaged components	Install water permeable fences around storage tanks to catch small-to-medium sized debris, elevate tank, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
Machinery	Water damage to electrical components & machinery	Reinstate or replace	Stockpile spare parts outside of expected inundation zone, make pre-disaster arrangements to move equipment to higher ground if possible, store equipment on high ground where possible, install flood controls	Low	(Edwards 2006; American Society of Civil Engineers 2005)
	Complete damage/washout	Recover equipment, replace equipment	Make pre-disaster arrangements to secure or elevate machinery if possible, store in RC design buildings, store equipment on high ground where possible	Low	(Horspool & Fraser 2015; Cruz et al. 2009; PIANC Working Group 53 2009)
Pipes	Decoupling	Reinstate, temporary linkages, replace connectors	Use HDPE pipes, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers	Low	(Horspool & Fraser 2015; Miyajima 2014; Bell et al. 2005; Scawthorn et al. 2006; American Society of Civil Engineers 2005; Matsuhashi et al. 2012; Edwards 2006)
	Washout of pipes over waterway	Lay temporary supports and new pipe, attach new or temporary pipes to existing or temporary bridges, rebuild utility bridge	Burry beneath waterway if possible, elevate utility bridges, attach to RC bridge, use protection buffers, use HDPE pipe, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers	Low	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
	Scour of backfill	Replace backfill	Use well compacted material, set back from coast if possible, use erosion protection	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Francis 2006)
	Complete damage/washout	Lay temporary HDPE pipes, replace pipes, deploy water trucks	Stockpile spare parts outside of expected inundation zone, use HDPE pipes, develop rapid response plans to deploy repair workers & water trucks, use erosion protection	Low	(Horspool & Fraser 2015; Miyajima 2014; Matsuhashi et al. 2012; Edwards 2006; Bell et al. 2005; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Scawthorn et al. 2006; Francis 2006)
Pumping Stations	Salt water contamination	Shut off intakes, reinstate or replace equipment and filters	Seal openings, make pre-disaster arrangements to shut off intake facilities, locate outside of expected inundation zone if possible, make arrangements to cover intakes if possible	Low	(Horspool & Fraser 2015; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005; Bell et al. 2005)
	Sediment & debris cover	Clear by hand or with heavy machinery	install water permeable fences around facilities to catch small-to-medium sized debris, use water tight housing, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or replace damaged components	install water permeable fences around facilities to catch small-to-medium sized debris, elevate facilities, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009)
	Water damage to electrical components	Replace damaged components	Stockpile spare parts outside of expected inundation zone, water tight housing for electronic panels, elevate electrical components, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Unjoh 2012; McClelland 2011; Edwards 2006; Bell et al. 2005; Scawthorn et al. 2006; Nakanishi et al. 2014; PIANC Working Group 53 2009; Cruz et al. 2009; American Society of Civil Engineers 2005)
	Complete damage/washout	Deploy temporary pumps, reinstate, replace	Stockpile spare pumps outside of expected inundation zone, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; Cruz et al. 2009; American Society of Civil Engineers 2005)
<u>*Flood Controls*</u> *Stop Banks*	Scour	Replace material, reinstate, rebuild	Use erosion protection on embankments, vegetate embankments, design to withstand hydrodynamic forces from both sides, Build up any gaps in structure	Low	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)
	Complete damage/washout	install temporary stop banks, rebuild	Use erosion protection, vegetate embankments, design to withstand hydrodynamic forces from both sides, build up any gaps in structure	Low	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)
Walls & Floodgates	Scour of foundations	Replace material if foundations undamaged, rebuild structure	Use deep concrete foundations, use well compacted backfill material, build up gaps in structure, implement overlapping walls at openings	Medium	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)
	Complete damage/washout	Rebuild	Use deep concrete foundations, use well compacted backfill material, avoid gaps in structure, overlap walls at openings, use RC design, install bumpers, reinforce structure on both sides	Medium	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)

Coastal Management					
Sea Walls	Scour of foundations	Replace material if foundations undamaged, rebuild structure	Use deep concrete foundations, use well compacted backfill material, build up any gaps in structure, utilise overlapping walls at openings, reinforce structure, install breakwaters	Medium	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)
	Complete damage/washout	Rebuild	Use deep concrete foundations, use well compacted backfill material, build up any gaps in structure, overlap walls at openings, use RC design, install bumpers, reinforce structure on both sides, install breakwaters	Medium	(Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; Hart & Knight 2009; Iemura et al. 2005; PIANC Working Group 53 2009)
Breakwaters	Scour	Replace material	Maintain structure, design to withstand tsunami induced hydrodynamic forces, increase erosion protection	Low	(American Society of Civil Engineers 2005; Cruz et al. 2009; Edwards 2006; Francis 2006)
	Complete damage/washout	Rebuild	Maintain structure, design to withstand tsunami induced hydrodynamic forces, increase erosion protection	Low	(American Society of Civil Engineers 2005; Cruz et al. 2009; Edwards 2006; Francis 2006)
	Sliding of caissons	Reinstate	Design to withstand tsunami induced hydrodynamic forces	Low	(American Society of Civil Engineers 2005)
Dunes and Embankments	Scour	replace material, reinstate, rebuild	Plant vegetation, plant control forests, maintain natural dunes, build up any gaps in structure, install erosion protection on both sides, install breakwaters	Medium	(Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Francis 2006)
	Complete damage/washout	Rebuild, promote natural dune recovery	Plant vegetation, plant control forests, maintain natural dunes, build up gaps in structure, install erosion protection on both sides, install breakwaters	Medium	(Suppasri et al. 2013; Edwards 2006; Cruz et al. 2009; Hart & Knight 2009; Kurian et al. 2007; PIANC Working Group 53 2009; American Society of Civil Engineers 2005; Francis 2006)
Telecoms					
Wireless					
Cellular Towers	Scour of foundations	Replace backfill if foundations undamaged, stabilise or relay foundations if necessary, use temporary supports	Use deep concrete foundations, use well compacted backfill, attach tower to multi-storey RC design building, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Debris strikes	Reinstate if necessary, replace if damage is structural	Install protection bumpers, use RC design, mount on multi-storey RC design building, use monopole structure, install water permeable fences around facilities to catch small-to-medium sized debris	Low	(Horspool & Fraser 2015; LRFD 2010; Iemura et al. 2005; Kwasinski 2013; Cutter et al. 2008)
	Water damage to electrical components and base station	Redirect traffic to undamaged sites, reinstate, replace damaged electronics, deploy mobile cell sites & generators	Elevate components, use water tight housing on electrical components, stockpile spare parts outside of expected inundation zone, develop rapid response plans to deploy repair workers, locate outside of expected inundation zone if possible	Medium	(Horspool & Fraser 2015; Matsuhashi et al. 2012; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; Sagara & Ishiwatari 2012; Unjoh 2012; Scawthorn et al. 2006; Bell et al. 2005; Cruz et al. 2009)
	Complete damage/washout	Redirect traffic to undamaged sites, increase coverage radius of un-damaged sites, deploy mobile cell sites, use temporary cell sites, rebuild	Use deep concrete foundations, use RC design monopole structure, mount tower on multi-storey RC buildings, stockpile mobile cell sites & other spare parts outside of expected inundation zone, make rapid response plans to deploy mobile cell sites & generators, locate outside of expected inundation zone if possible	Medium	(Horspool & Fraser 2015; Matsuhashi et al. 2012; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; Sagara & Ishiwatari 2012; Unjoh 2012; Scawthorn et al. 2006; Bell et al. 2005; Evans & McGhie 2011)
Exchange Centres	Water damage to interiors and equipment	Use temporary exchanges, use backup generators, reinstate or replace components	Install water tight doors, locate outside of expected inundation zone if possible, elevate exchange centre, use water tight housing on electrical panels, elevate generators, locate in multi-storey RC building, stockpile mobile temporary exchange centres outside of expected inundation zone	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Cruz et al. 2009; Matsuhashi et al. 2012; Kwasinski 2013; McClelland 2011; Scawthorn et al. 2006)
	Scour of foundations	Reinstate severed connections, replace backfill	Use well compacted material, use deep concrete foundations, install erosion protection and flood controls, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; Bell et al. 2005; LRFD 2010)
	Complete damage/washout	Use temporary satellite entrance links, use temporary exchange centres, deploy mobile microwave repeaters	Locate outside of expected inundation zone, use multi-storey RC design, stockpile mobile temporary exchange centres and microwave repeaters outside of expected inundation zone, locate outside of expected inundation zone if possible	Medium	(Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; Cruz et al. 2009; PIANC Working Group 53 2009; Edwards 2006; American Society of Civil Engineers 2005)
Radio Transmitters	Scour of foundations	Replace backfill if foundations undamaged, stabilise or relay foundations if necessary, use temporary supports	Use deep concrete foundations, use well compacted backfill, attach tower to multi-storey RC design building, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Edwards 2006; King & Bell 2006; Francis 2006; LRFD 2010; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)
	Debris strikes	Reinstate or repair if necessary, replace if damage is structural	Install protection bumpers, use RC design, mount on multi-storey RC building, use monopole structure, install water permeable fences around facilities to catch small-to-medium sized debris, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; LRFD 2010; Iemura et al. 2005; Kwasinski 2013; Cutter et al. 2008)
	Complete damage/washout	Use temporary transmitter towers, rebuild, attach transmitters to non-damaged structures	Install long range radio transmitters & stockpile temporary transmitters outside of expected inundation zone, use deep concrete foundations, use RC design monopole structure, mount tower on multi-storey RC buildings, locate outside of expected inundation zone if possible	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; PIANC Working Group 53 2009)

Internet					
Overhead Cables	Foundation scour	Repair foundations, replace backfill if foundations undamaged	Bury cables, use deep concrete foundations, use well compacted backfill material	Medium	(Horspool & Fraser 2015; McClelland 2011; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Bell et al. 2005; Francis 2006; LRFD 2010)
	Debris strikes	Replace damaged supports, replace severed cables, deploy mobile satellite link Wi-Fi hotspots	Bury cables, elevate cables, make rapid response plans to deploy repair workers, stockpile spare parts outside of expected inundation zone	Low	(Horspool & Fraser 2015; Kwasinski & Tang 2012; Kwasinski 2013; McClelland 2011; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006)
	Complete damage/washout	Deploy satellite link mobile Wi-Fi hotspots, redirect traffic to undamaged networks, erect temporary supports, replace supports, replace cables	Bury cables, use RC design utility poles with deep concrete foundations, stockpile mobile satellite link hotspots & spare parts outside of expected inundation zone	Medium	(Horspool & Fraser 2015; Kwasinski 2013; Kwasinski & Tang 2012; McClelland 2011; Scawthorn et al. 2006; Edwards 2006; American Society of Civil Engineers 2005)
Buried Cables	Scour of backfill	Replace backfill	Use well compacted backfill material, use erosion protection	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Francis 2006)
	Cables and ducting across waterways severed	Use temporary supports, mount to temporary or existing bridges, rebuild utility bridge, deploy mobile satellite link Wi-Fi hotspots	Install protection bumpers, elevate supports, use deep concrete foundations, mount to RC bridge, bury beneath waterway if possible	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
Switch Boxes	Water damage to internal components	Replace damaged components, deploy satellite link mobile Wi-Fi hotspots	Stockpile spare parts & mobile satellite link hotspots outside of expected inundation zone, elevate on supports, install watertight seal on switch box housing	Medium	(Horspool & Fraser 2015; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)
	Debris strikes	Repair damaged components, replace unit	Install protection bumpers, elevate on supports or multi-storey RC design building, stockpile spare parts & units outside of expected inundation zone	Low	(Horspool & Fraser 2015; Iemura et al. 2005; LRFD 2010; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)
	Complete damage/washout	Deploy satellite link mobile Wi-Fi hotspots, use temporary exchanges, replace unit	Elevate on supports, bury, anchor to foundations, reinforce switch box housing, mount to RC design buildings, stockpile spare units outside of expected inundation zone, locate outside of expected inundation zone	Low	(Horspool & Fraser 2015; Iemura et al. 2005; LRFD 2010; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005; Scawthorn et al. 2006)
Landline					
Overhead Cables	Foundation scour	Repair foundations, replace backfill if foundations undamaged	Bury cables, use deep concrete foundations, use well compacted backfill material	Medium	(Horspool & Fraser 2015; McClelland 2011; Kwasinski 2013; Edwards 2006; American Society of Civil Engineers 2005; Bell et al. 2005; Francis 2006; LRFD 2010)
	Debris strikes	Replace damaged supports, replace severed cables	Bury cables, elevate cables, make rapid response plans to deploy repair workers, stockpile spare parts outside of expected inundation zone	Low	(Horspool & Fraser 2015; Kwasinski & Tang 2012; Kwasinski 2013; McClelland 2011; Edwards 2006; American Society of Civil Engineers 2005; Sagara & Ishiwatari 2012; Unjoh 2012; Bell et al. 2005; Scawthorn et al. 2006)
	Complete damage/washout	Redirect traffic to undamaged networks, erect temporary supports, replace supports, replace cables, utilise wireless network if available	Bury cables, use RC design utility poles with deep concrete foundations, stockpile spare parts outside of expected inundation zone	Medium	(Horspool & Fraser 2015; Kwasinski 2013; Kwasinski & Tang 2012; McClelland 2011; Edwards 2006; American Society of Civil Engineers 2005)
Buried Cables	Scour of backfill	Replace backfill if cables undamaged	Use well compacted backfill material, use erosion protection	Low	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Francis 2006)
	Cables and ducting across waterways severed	Use temporary supports, mount to temporary or existing bridges, rebuild utility bridge, utilise wireless network if available	Install bumpers, elevate supports, use deep concrete foundations, mount to RC bridge, bury beneath waterway if possible	Medium	(Horspool & Fraser 2015; Sagara & Ishiwatari 2012; Akiyama et al. 2013; Saatcioglu 2007; Tang & Edwards 2012; American Society of Civil Engineers 2005; Edwards 2006; Scawthorn et al. 2006; Iemura et al. 2005; LRFD 2010)
Exchange Centres	Water damage to interiors and equipment	Use mobile temporary exchange centre, use backup generators, reinstate or replace components, utilise wireless network if available	Install water tight doors, locate outside of expected inundation zone, elevate exchange centre, use water tight housing on electrical panels, elevate generators, locate in multi-storey RC design building	Medium	(Horspool & Fraser 2015; Edwards 2006; American Society of Civil Engineers 2005; Cruz et al. 2009; Matsuhashi et al. 2012; Kwasinski 2013; McClelland 2011; Scawthorn et al. 2006)
	Scour of foundations	Reinstate any severed lifeline connections, replace backfill	Use well compacted backfill material, use deep concrete foundations, install erosion protection & flood controls	Low	(Horspool & Fraser 2015; Edwards 2006; Francis 2006; American Society of Civil Engineers 2005; Bell et al. 2005; LRFD 2010)
	Complete damage/washout	Use mobile temporary exchange centre, replace, utilise wireless network if available	Locate outside of expected inundation zone, use multi-storey RC design building, stockpile mobile temporary exchange centres & microwave repeaters outside of expected inundation zone	Medium	(Horspool & Fraser 2015; Kwasinski & Tang 2012; McClelland 2011; Tang & Edwards 2012; Cruz et al. 2009; PIANC Working Group 53 2009; Edwards 2006; American Society of Civil Engineers 2005)
Switch Boxes	Water damage to internal components	Replace damaged components, utilise wireless network if available	Stockpile spare parts outside of expected inundation zone, elevate on supports, install water tight seal on switch box housing	Medium	(Horspool & Fraser 2015; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)

	Debris strikes	Repair damaged components, replace unit	Install protection bumpers, elevate on supports or multi-storey RC design building	Low	(Horspool & Fraser 2015; Iemura et al. 2005; LRFD 2010; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005)
	Complete damage/washout	Use temporary exchanges, replace unit, utilise wireless network if available	Elevate on supports, bury unit, anchor to foundations, reinforce switch box housing, mount to RC design buildings, stockpile spare parts & units outside of expected inundation zone, locate outside of expected inundation zone if possible	Low	(Horspool & Fraser 2015; Iemura et al. 2005; LRFD 2010; Matsuhashi et al. 2012; Kwasinski 2013; Kwasinski & Tang 2012; Edwards 2006; American Society of Civil Engineers 2005; Scawthorn et al. 2006)